AN EXPERIMENTAL INVESTIGATION OF THE
TRANSIENT RESPONSE TIME OF A SIMULATED SUPERSONIC
WIND TUNNEL PRESSURE INSTRUMENTATION SYSTEM

12T-R

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by

Neil A. Clanton

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Approved:

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NOTATION

d inside diameter of capillary tubing.

d_c inside diameter of connecting tubing.

d_o orifice diameter.

Hg mercury.

ℓ length of capillary tubing.

ℓ_c length of connecting tubing.

mmf micromicro-farad.

p_ℓ line pressure.

p_r reservoir pressure.

τ response time required for the pressure sensitive instrument to reach a point within one per cent of the reservoir pressure.

τ_1 response time required for the pressure sensitive instrument to reach a point within two and one-half per cent of the reservoir pressure.

τ_2 response time required for the pressure sensitive instrument to reach a point within five per cent of reservoir pressure.

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SUMMARY

In this report an experimental analysis of the transient response time of a supersonic wind tunnel pressure instrumentation system was made. The response time for the system was defined as the time required for the pressure sensitive device to reach a point within one per cent of the reservoir pressure.

The purpose of this paper was to extend the limited data available on the design of such installations. This aim was accomplished by experimentally determining the response time of a system which closely simulated a supersonic wind tunnel pressure system. The installation used consisted of an orifice, capillary tubing, connecting tubing, and a mercury manometer which was used to simulate the pressure measuring device.

Five parameters, which largely determine the response time of the pressure system, were analyzed individually and their effects determined. These factors were

1. Capillary tube diameter
2. Capillary tube length
3. Connecting tube length
4. Reservoir pressure
5. Initial line pressure.

The results obtained in this work show that the cap-

illary tubing and the connecting tubing should be kept as short as possible if static pressures below ten millimeters of mercury are to be measured. For larger reservoir pressures the optimum tube diameter was found to be approximately 0.042 inches. The initial line pressure was found to have very little effect on the response time of the system.

Qualitative comparison of the results of this work with that of reference 2 shows good correlation.

CHAPTER I

INTRODUCTION

In the design of present day high speed aircraft, missiles, etc., it is necessary to supplement theoretical design procedures with extensive wind tunnel tests. The determination of the pressure distributions over the surface of the wind tunnel model is of paramount importance in order that load distributions may be determined. To obtain these pressure distributions, a measuring system that is capable of transmitting the model pressures to some pressure sensitive device located external to the test section must be designed. Since at the start of each test run a pressure differential will exist between the test section and the recording instrument, each run must be of sufficient length for the transient response produced by the step pressure differential to dissipate.

The purpose of this report is to extend the available pressure instrumentation design criteria by experimentally determining the effects of varying the important parameters which, to a large extent, determine the response time of the system. The simulated pressure system used in this experimental analysis is typical of those employed in present supersonic wind tunnel tests. This system, which is shown schematically in Fig. 1, consists of an orifice, model tubing, connecting tubing, and a mercury manometer which serves as the pressure measuring device. The response time for the system is considered to be that time required for the pressure sensitive device to reach a point within one per cent of the equilibrium pressure.

The importance of careful design to minimize the response time for a given system becomes apparent when the two most prevalent types of wind tunnels currently in use are studied. These two types are the continuous tunnel and the intermittent tunnel. In the continuous tunnel, supersonic flow is maintained throughout a series of runs and to obtain maximum operating efficiency the individual runs should be as short as possible. A knowledge of the response time is obviously necessary if reliable data is to be obtained while running time is held to a minimum. In the case of the intermittent wind tunnel, response time is even more critical than with the continuous tunnel. Because of the tremendous power requirements and the accompanying high operating costs, supersonic wind tunnels tend to have small test sections. This means that the orifice and model tubing diameters must be small. Thus the flow of air through the lines is restricted and often leads to very large response times. In extreme cases the response time may exceed the running time for the intermittent tunnel.

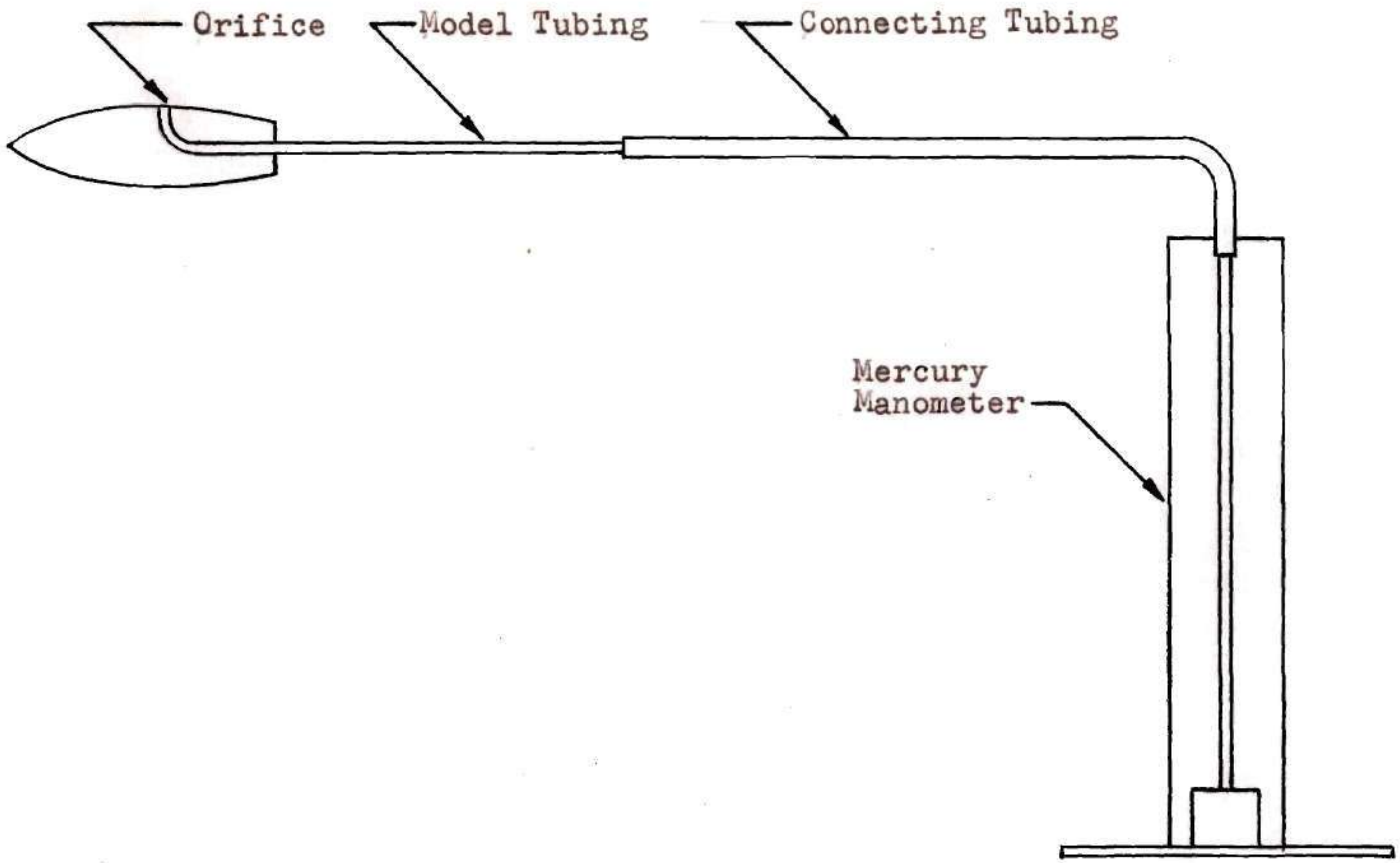


Figure 1. Schematic Diagram of Typical Pressure System

A search of the literature pertaining to transient response time in supersonic wind tunnel pressure systems revealed that data on this subject is extremely limited.

Kendall (1) was the first to attempt a solution to this time lag problem. He assumed the flow through capillary tubing could be approximated analytically by a quasi-steady state solution of the compressible Poiseuille flow equations. Since this solution did not account for the initial transient states its use is confined primarily to the continuous operating wind tunnel where a few seconds error in response time can be tolerated.

The first comprehensive analytical and experimental work in this field was done by Ducoffe (2). In this investigation the analytical solution was made assuming that quasi-steady, developed flow existed throughout the length of the tubing, that changes of state took place isothermally, and that a continuum flow existed. Extensive experimental work was done to evaluate the influence of the important parameters on the response time and also to correlate the theory. The purpose of this work was to set up standards for the optimum design of pressure measuring systems having pressure sensing elements with essentially zero time lag. The work done in the present report is primarily a continuation of the work done by Dr. Ducoffe with a mercury manometer substituted for the pressure capsule used in the original work.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

The physical setup for this experimental analysis was designed to simulate a supersonic wind tunnel instrumentation system. For purposes of clarity the description of the equipment has been divided into three sections. These subdivisions are: (1) the vacuum system, (2) the simulated pressure system, and (3) the electronic system used to measure and record the data. This experimental equipment is shown in Figs. 2 and 3.

Vacuum system.--The vacuum system which is shown schematically in Fig. 4, consists of a large reservoir, a differential U tube manometer and two vacuum pumps. The reservoir was a large steel tank three feet in diameter and seven and one-half feet long having a volume of fifty-three cubic feet which simulated the wind tunnel test section. This large volume made it possible to make constant reservoir pressure runs at reservoir pressures as low as five millimeters of mercury absolute.

The vacuum pump used to obtain the desired reservoir pressures was an Excelsior Rotary Pump manufactured by the Foster Pump Works, Incorporated. The pump was connected through a gate valve to the pressure reservoir and was cap-

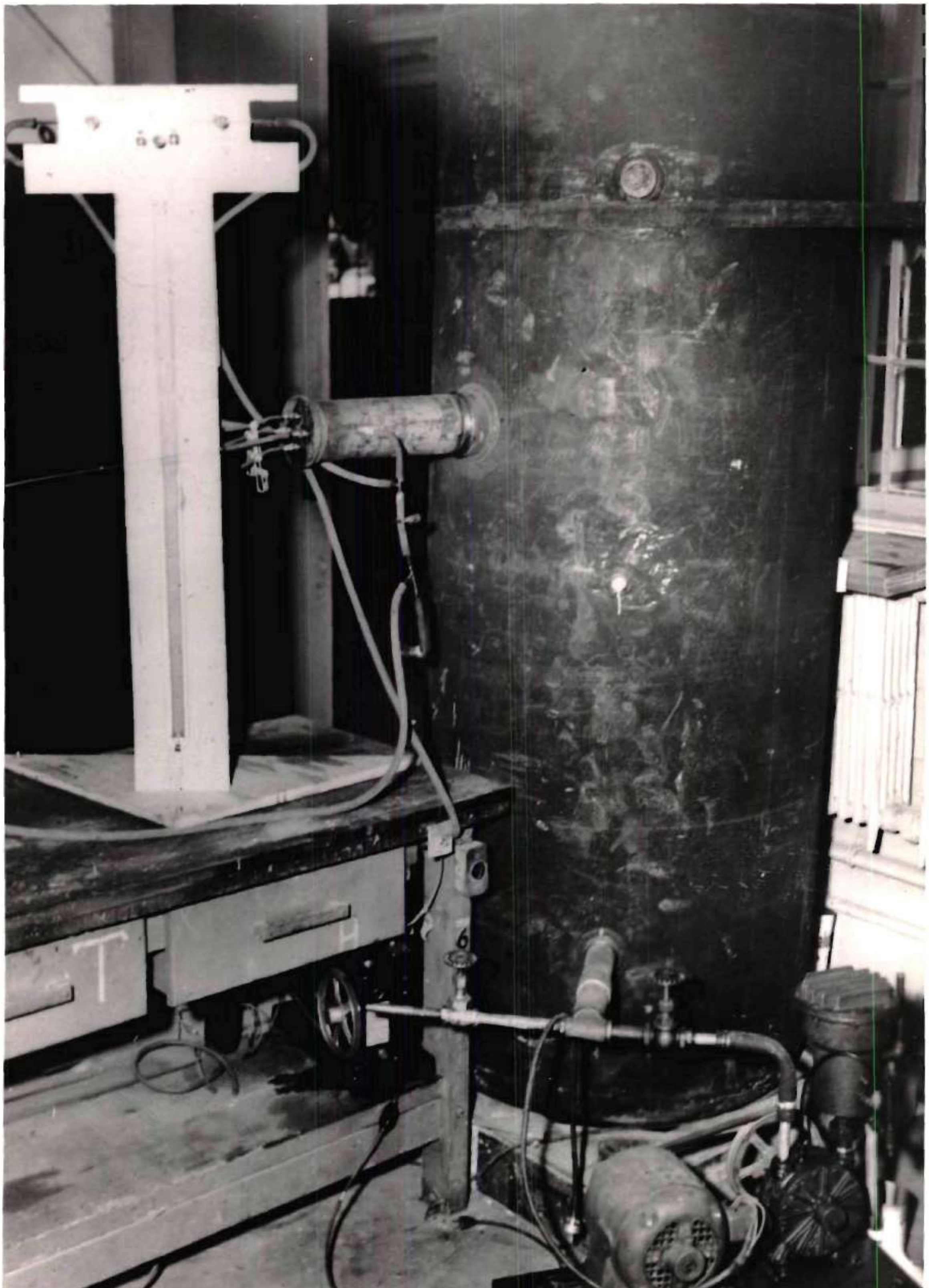


Figure 2. Vacuum System

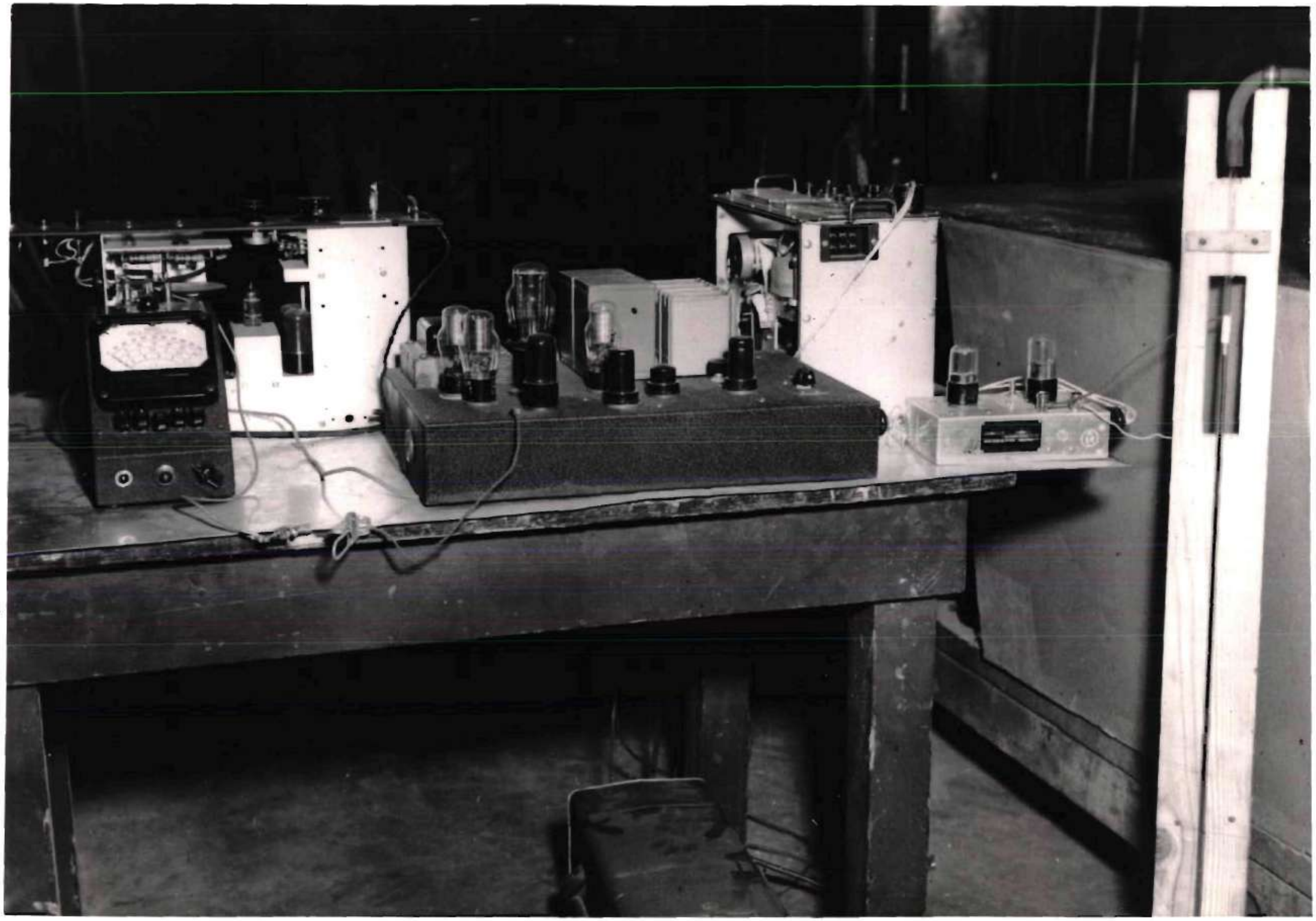


Figure 3. Electronic Measuring Equipment

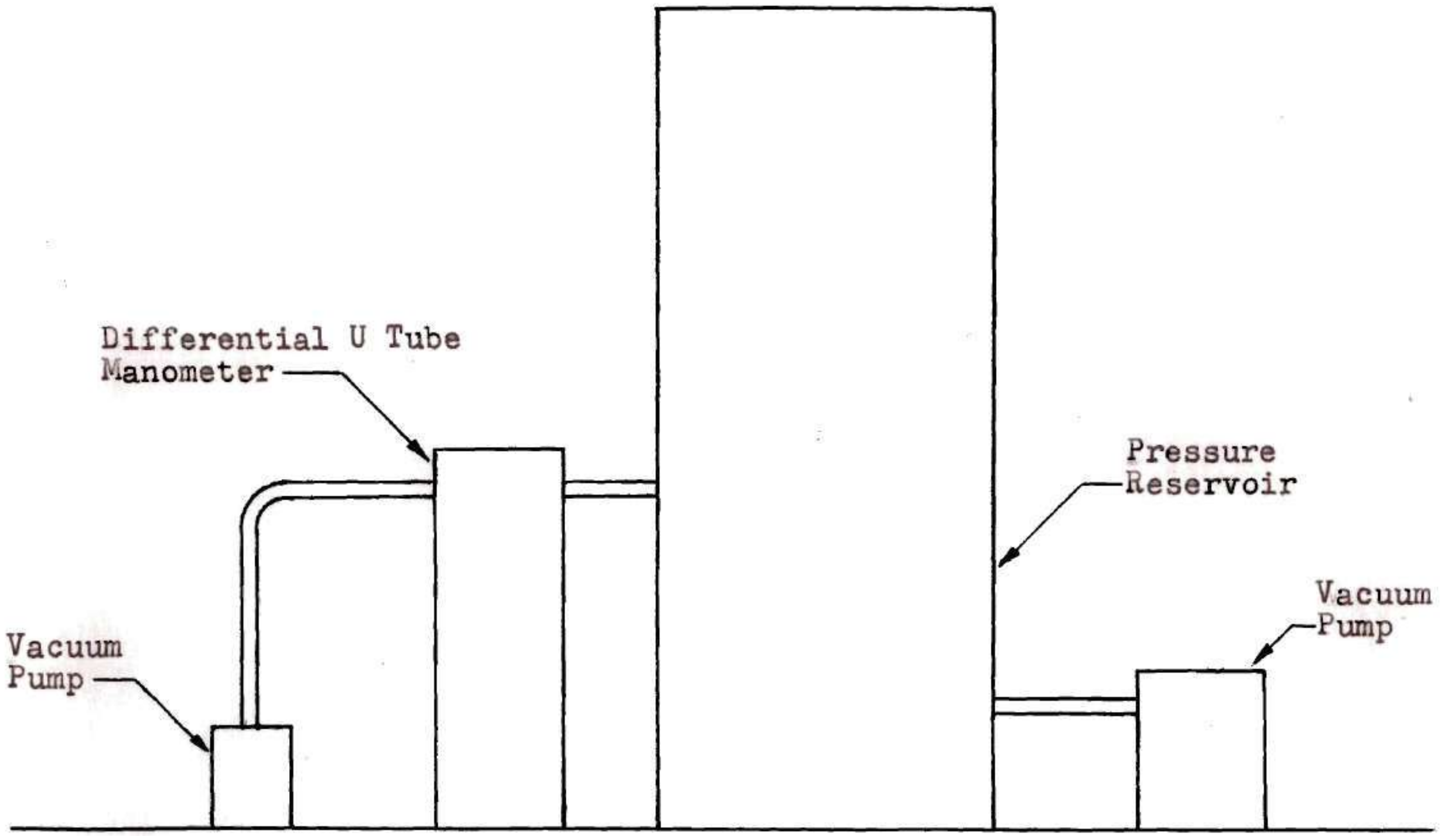


Figure 4. Schematic Diagram of Vacuum System

able of developing absolute tank pressures of five millimeters of mercury which was the minimum pressure required for this analysis.

The differential U tube manometer was used to measure the reservoir and line pressures. The liquid used in the manometer was dibutyl-phthalate which is an oil having a low vapor pressure and a density of 1.0421 at twenty-five degrees centigrade. A careful investigation of the variation of the density ratio of this oil and mercury with temperature gave a constant ratio of thirteen to one. This resulted in an expanded scale which made it possible to read reservoir and line pressures to an accuracy of $\pm$ 0.077 millimeters of mercury. Operation of the U tube manometer was accomplished by connecting one side of the tube to a rotary vacuum pump which was capable of developing pressures of a tenth of a micron of mercury. The pump used was a Duo Seal Vacuum Pump manufactured by the Welch Manufacturing Company. This pump gave a reference pressure on one side of the tube which was well within the desired accuracy of the system. The other side of the U tube was connected through a copper T to the pressure reservoir. The purpose of this T was to establish an outlet for an auxiliary line which was needed to set line pressures. A complete explanation of the use of this line is given in Chapter III.

<u>Simulated pressure instrumentation system</u>.--The pressure

system, Fig. 5, was simulated by connecting the mercury manometer (pressure sensitive device) to the pressure reservoir by means of connecting tubing, capillary tubing (model tubing), and an orifice.

The orifice housing was fitted and soldered in a flared-tube nut. This nut was connected by a tube union to a face plate which was mounted on a five inch steel outlet to the pressure reservoir. Four holes were drilled and tapped in the face plate for the four orifice sizes available; however, in this analysis an orifice diameter of 0.025 in. was used for all tests. A short length of copper tubing 0.125 O.D. by 0.067 I.D. in. was soldered into the orifice housing to serve as a connection for the capillary tubing.

The model tubing was simulated by stainless-steel hypodermic needle tubing. This capillary tube joined the orifice to the connecting tube. Copper nipples were soldered on each end of the tube to facilitate connections which were made with short lengths of thick-walled rubber tubing. In order to prevent leaks, the connections were coated with a clear varnish (glyptal) manufactured by the General Electric Company.

The connecting tube was 0.125 in. I.D. by 0.5 in. O.D. micropure gum vacuum tubing. This tubing was used to connect the capillary tube to the pressure sensitive device (mercury manometer) through a copper T. This T served as

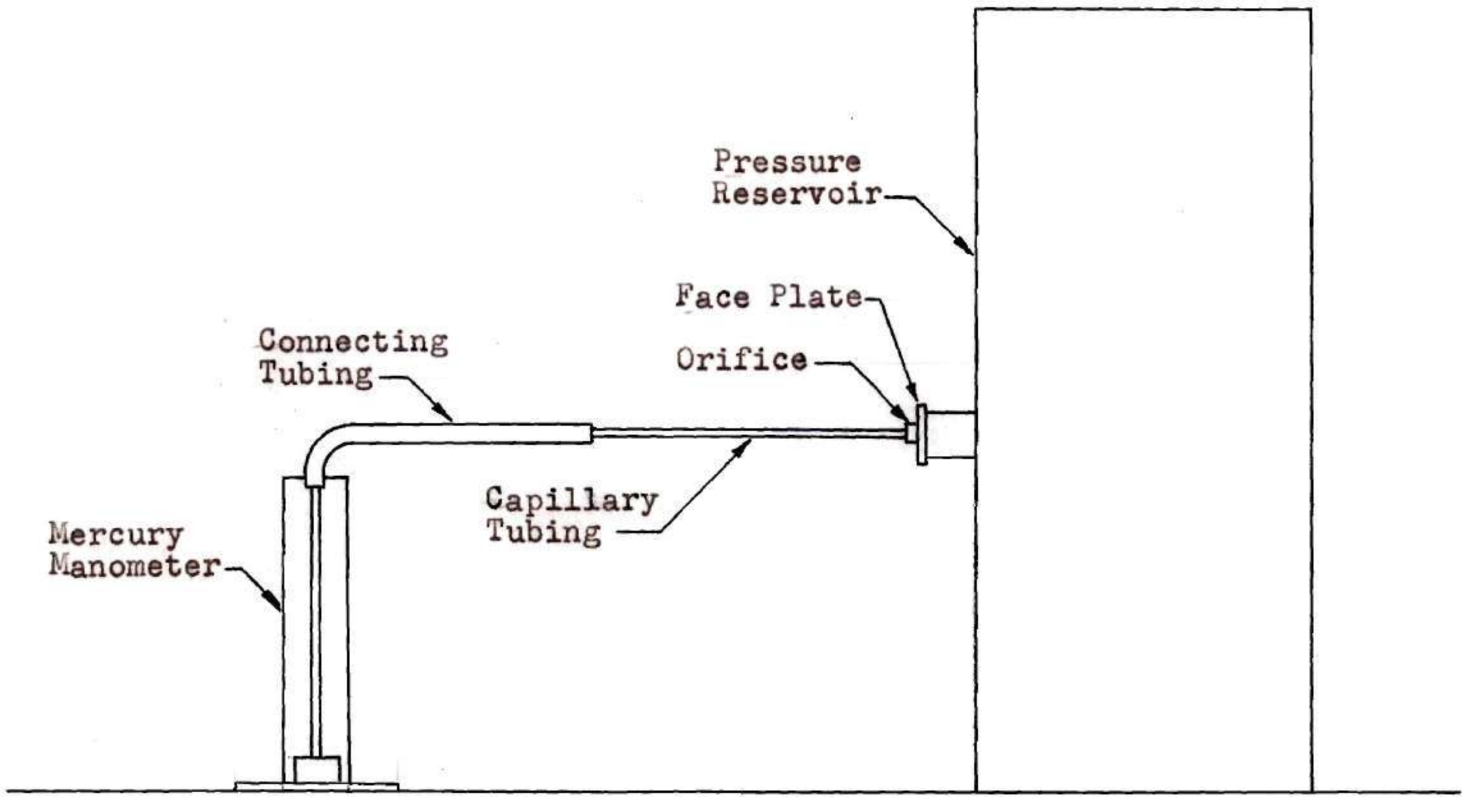


Figure 5. Schematic Diagram of Simulated Pressure System

the other outlet for the previously mentioned auxiliary line. Glyptal was again used on all connections.

The pressure sensitive instrument consisted of a 0.250 O. D. by 0.141 I. D. glass tube inserted in a covered mercury bath. The cover was slotted so that atmospheric pressure was maintained at all times on the mercury. The top of this tube was connected to the pressure reservoir by the connecting and capillary tubing.

Electronic system.--The electronic system used to measure the variation in height of the mercury in the manometer consisted of an oscillator, measuring capacitors, an a-c preamplifier, a discriminator and d-c output amplifier, a Sanborn recorder with its d-c amplifier, and a voltage regulated power supply. This system measured and traced out time histories of the deviation of the pressure from equilibrium position. A block diagram of this system is shown in Fig. 6.

The oscillator unit consisted of a Wien Bridge Oscillator and a cathode follower. The oscillator developed an 1100 cycle signal which was fed through a voltage divider network to the grid of the cathode follower. The voltage divider consisted of a fixed 30 mmf. capacitor and a variable capacitor. One plate of the variable capacitor was the mercury column and the other plate was an aluminum foil strip attached to the outside of the glass tubing. The magnitude of this capacitor was approximately 40 mmf. The voltage ap-

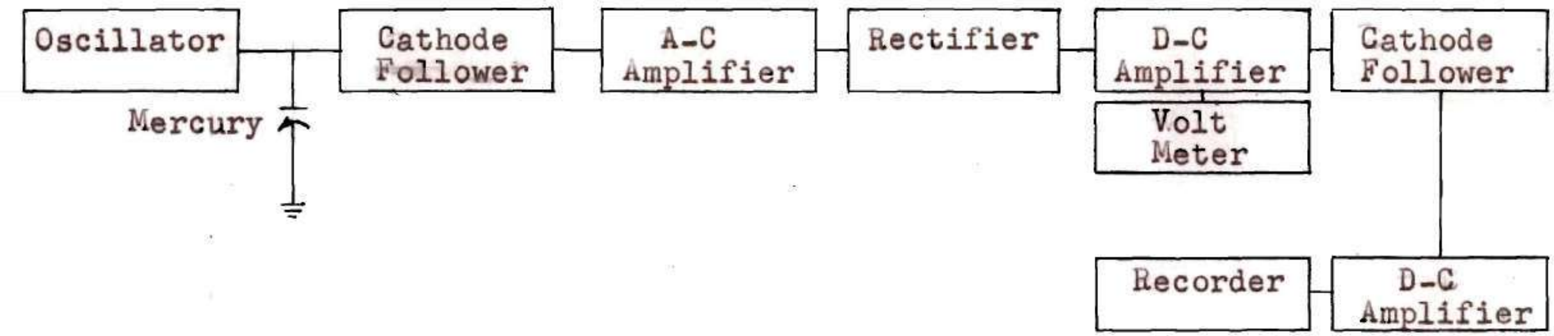


Figure 6. Block Diagram of Electronic Measuring System

plied to the grid of the cathode follower was a function of the height of the mercury column. The plate voltage for the oscillator and the cathode follower was obtained from a 255 volt regulated power supply. The purpose of the cathode follower was to prevent any stray pickup or line voltage changes from affecting the variable voltage of the input to the a-c amplifier.

The low impedance output of the cathode follower was fed to a triode a-c amplifier tube with a voltage gain of approximately fifty to one. The output of the a-c amplifier was then fed to a diode rectifier. The d-c voltage developed by this detector was approximately minus fifteen volts. Since this voltage will drive the first d-c amplifier into cutoff, a positive voltage of approximately twelve volts was also applied to the grid of the first d-c amplifier. A voltmeter and a variable control were inserted into the system at this point. This control served a twofold purpose. The positive grid voltage could be adjusted to a linear portion of the d-c amplifier characteristic curve and the gain of the system could be maintained at a constant value for different mercury levels. The grid voltage of the first d-c amplifier was therefore directly proportional to the change in the height of the mercury column. This changing voltage was further amplified and fed through a cathode follower to the Sanborn d-c amplifier. The steady state output of the d-c amplifier system was balanced by a fixed battery. Therefore the only output that appeared at the terminals of the Sanborn amplifier was the change in voltage due to the change in the mercury level from the equilibrium position. This oscillator and a-c d-c amplifier was designed especially for this system.

Increased sensitivity was obtained by use of a Sanborn d-c amplifier. The amplified voltage was then fed into the Sanborn recorder which converted the electrical signal to a mechanical deflection of the recorder stylus. The purpose of the recorder was to trace out a time history of the mercury movement from its initial position until the equilibrium state was reached.

The power supplies for the oscillator, the a-c d-c amplifier, and the cathode followers were regulated by the use of voltage regulator tubes. The a-c power supplied for the entire system was fed through a voltage regulating transformer.

CHAPTER III

TESTS AND PROCEDURE

Tests

Five important parameters which largely govern the operating characteristics of a supersonic wind tunnel pressure instrumentation system have been investigated in this report. These five parameters are:

1. Capillary tube diameter
2. Capillary tube length
3. Connecting tube length
4. Reservoir pressure
5. Initial line pressure.

It should be noted that the above listed parameters do not represent a complete list of the factors which affect the operation of the pressure measuring system. A brief discussion of the influence of the remaining parameters can be found in Chapter IV.

In order to determine the effects of each of the parameters, a series of tests were made in which all factors were held constant except the one under investigation. In all cases values were chosen that are representative of those found in currently operating wind tunnels.

<u>Capillary tube diameter</u>.--The size of the model tubing is

largely determined by the number of orifices required, the size of the model and the size of the sting support through which the pressure lines must be taken out of the model. Since the power required to operate a supersonic wind tunnel increases tremendously as the size of the test section is increased, the average test section is usually small. This results in small models and small sting supports. Thus, in order to obtain sufficient pressure data, that is, a large number of pressure orifices, the model tube diameter must be held to a minimum size. The diameters chosen for these tests were 0.063 in., 0.054 in., 0.042 in., 0.031 in., and 0.025 in. Table 1 summarizes the runs made to determine the diameter effect.

Capillary tube length.--The length of the capillary tubing is again a function of model size. The range of lengths selected here was two, four, six, and eight feet which should cover current installations. A list of the runs to determine the length effects is given in Table 2.

Connecting tube length.--The connecting tube must be sufficiently long to connect the capillary tubing to the pressure sensitive device. This tube length should be as short as possible in order to minimize the mass that must be evacuated from the lines before equilibrium can be established. Lengths of zero, five, and ten feet with an inside diameter of 0.125 in. were chosen for these runs. An outline of these

Table 1. Capillary Tube Diameter Effects

d (in.)	d_o (in.)	ℓ (in.)	d_c (in.)	p_ℓ (mm Hg.)	p_r (mm Hg.)	ℓ_c (in.)
0.063	0.025	24	0.125	30	20	0
0.054	0.025	24	0.125	30	20	0
0.042	0.025	24	0.125	30	20	0
0.031	0.025	24	0.125	30	20	0
0.025	0.025	24	0.125	30	20	0
0.063	0.025	24	0.125	20	10	0
0.054	0.025	24	0.125	20	10	0
0.042	0.025	24	0.125	20	10	0
0.031	0.025	24	0.125	20	10	0
0.025	0.025	24	0.125	20	10	0
0.063	0.025	24	0.125	15	5	0
0.054	0.025	24	0.125	15	5	0
0.042	0.025	24	0.125	15	5	0
0.031	0.025	24	0.125	15	5	0
0.025	0.025	24	0.125	15	5	0

Table 2. Capillary Tube Length Effects

ℓ (in.)	d (in.)	d_o (in.)	d_c (in.)	p_ℓ (mm Hg.)	p_r (mm Hg.)	ℓ_c (in.)
24	0.063	0.025	0.125	30	20	0
24	0.054	0.025	0.125	30	20	0
24	0.042	0.025	0.125	30	20	0
24	0.031	0.025	0.125	30	20	0
24	0.025	0.025	0.125	30	20	0
48	0.063	0.025	0.125	30	20	0
48	0.054	0.025	0.125	30	20	0
48	0.042	0.025	0.125	30	20	0
48	0.031	0.025	0.125	30	20	0
48	0.025	0.025	0.125	30	20	0
72	0.063	0.025	0.125	30	20	0
72	0.054	0.025	0.125	30	20	0
72	0.042	0.025	0.125	30	20	0
72	0.031	0.025	0.125	30	20	0
72	0.025	0.025	0.125	30	20	0
96	0.063	0.025	0.125	30	20	0
96	0.054	0.025	0.125	30	20	0
96	0.042	0.025	0.125	30	20	0
96	0.031	0.025	0.125	30	20	0
96	0.025	0.025	0.125	30	20	0

tests can be found in Table 3.

Reservoir pressure.--The desired reservoir pressure is determined by the type of tunnel and the required Mach number. The reservoir pressures used in this investigation were five, ten, and twenty millimeters of mercury. For a stagnation pressure corresponding to atmospheric pressure the static pressure corresponding to a range $3.0 \leq M \leq 4.0$ was investigated. By increasing the stagnation pressure the Mach number range could be increased. These tests are summarized in Table 4.

Initial line pressure.--An increase in the initial line pressure causes a corresponding increase in the mass of air that must be removed from the instrument recording lines. Pressure differentials between the line and reservoir of five, ten, twenty, and thirty millimeters of mercury were tested to evaluate this effect. A complete list of these runs is given in Table 5.

Procedure

In order to facilitate the description of the procedure followed in obtaining the test data, a schematic diagram of the complete system is shown in Fig. 7. Frequent reference will be made to this figure in the following discussion.

The letters A through E represent the valves which control the flow through the lines. Prior to each series

Table 3. Connecting Tube Length Effects

l_c (in.)	d (in.)	l (in.)	d_c (in.)	p_l (mm Hg.)	p_r (mm Hg.)	d_o (in.)
0	0.063	24	0.125	30	20	0.025
0	0.054	24	0.125	30	20	0.025
0	0.042	24	0.125	30	20	0.025
0	0.031	24	0.125	30	20	0.025
0	0.025	24	0.125	30	20	0.025
60	0.063	24	0.125	30	20	0.025
60	0.054	24	0.125	30	20	0.025
60	0.042	24	0.125	30	20	0.025
60	0.031	24	0.125	30	20	0.025
60	0.025	24	0.125	30	20	0.025
120	0.063	24	0.125	30	20	0.025
120	0.054	24	0.125	30	20	0.025
120	0.042	24	0.125	30	20	0.025
120	0.031	24	0.125	30	20	0.025
120	0.025	24	0.125	30	20	0.025

Table 4. Reservoir Pressure Effects

p_r (mm Hg.)	d (in.)	d_o (in.)	d_c (in.)	ℓ (in.)	ℓ_c (in.)	p_ℓ (mm Hg.)
20	0.063	0.025	0.125	24	0	30
20	0.054	0.025	0.125	24	0	30
20	0.042	0.025	0.125	24	0	30
20	0.031	0.025	0.125	24	0	30
20	0.025	0.025	0.125	24	0	30
10	0.063	0.025	0.125	24	0	20
10	0.054	0.025	0.125	24	0	20
10	0.042	0.025	0.125	24	0	20
10	0.031	0.025	0.125	24	0	20
10	0.025	0.025	0.125	24	0	20
5	0.063	0.025	0.125	24	0	15
5	0.054	0.025	0.125	24	0	15
5	0.042	0.025	0.125	24	0	15
5	0.031	0.025	0.125	24	0	15
5	0.025	0.025	0.125	24	0	15

Table 5. Initial Line Pressure Effects

p_ℓ (mm Hg.)	d (in.)	d_o (in.)	d_c (in.)	ℓ (in.)	ℓ_c (in.)	pr (mm Hg.)
50	0.063	0.025	0.125	24	0	20
50	0.054	0.025	0.125	24	0	20
50	0.042	0.025	0.125	24	0	20
50	0.031	0.025	0.125	24	0	20
50	0.025	0.025	0.125	24	0	20
40	0.063	0.025	0.125	24	0	20
40	0.054	0.025	0.125	24	0	20
40	0.042	0.025	0.125	24	0	20
40	0.031	0.025	0.125	24	0	20
40	0.025	0.025	0.125	24	0	20
30	0.063	0.025	0.125	24	0	20
30	0.054	0.025	0.125	24	0	20
30	0.042	0.025	0.125	24	0	20
30	0.031	0.025	0.125	24	0	20
30	0.025	0.025	0.125	24	0	20
25	0.063	0.025	0.125	24	0	20
25	0.054	0.025	0.125	24	0	20
25	0.042	0.025	0.125	24	0	20
25	0.031	0.025	0.125	24	0	20
25	0.025	0.025	0.125	24	0	20

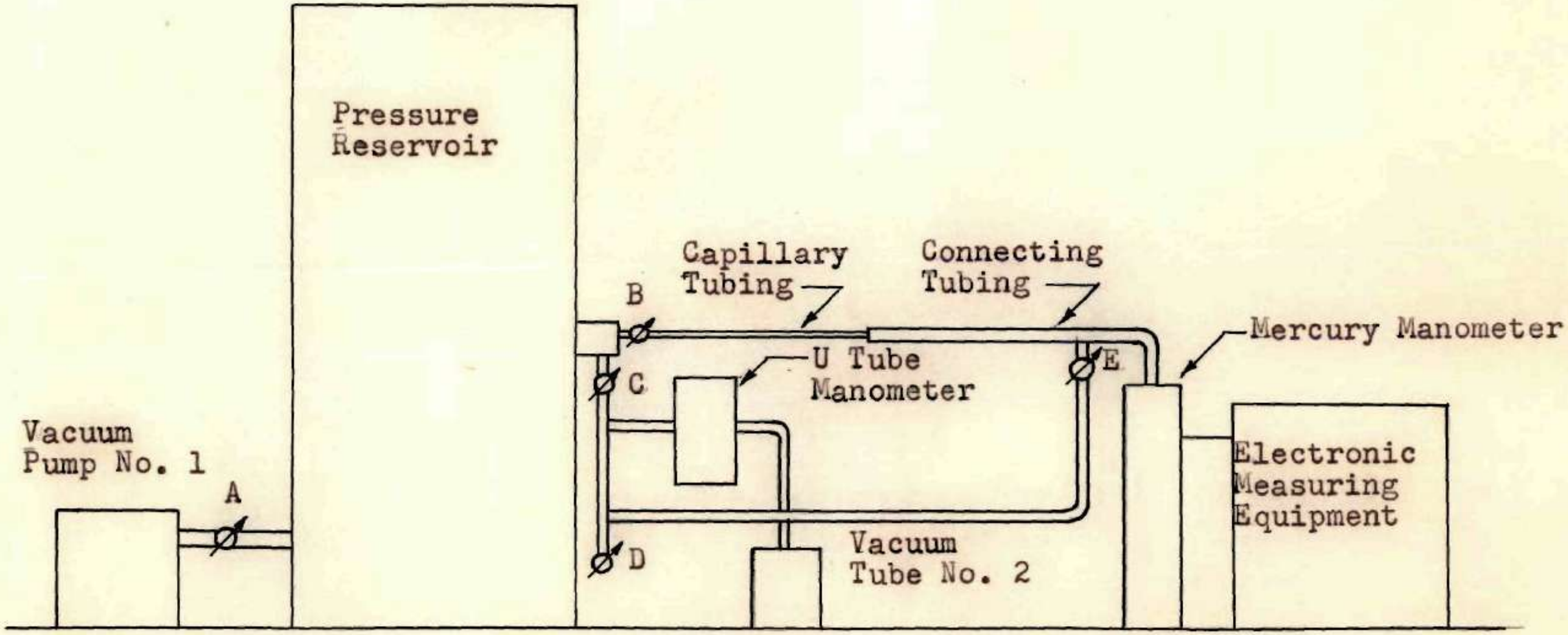


Figure 7. Schematic Diagram of Test Equipment

of runs, vacuum pump No. 1 was started and gate valve A was opened until the desired pressure was obtained in the reservoir. Vacuum pump No. 2 was operated at all times to maintain the reference pressure in one leg of the U tube manometer. The mercury level was adjusted to the center portion of the variable capacitor by raising or lowering the mercury manometer tube. The grid voltage was set to the desired value and the recorder was started to obtain an equilibrium trace. The recorder was then turned off and the valves B and C were closed. This isolated the pressure reservoir from the pressure instrumentation system. The bleed valve D was opened until the desired line pressure had been obtained through the auxiliary line and valve E was then closed to remove this line from the system. This gave a direct flow from the mercury manometer to the pressure reservoir. The actual run was started by opening valve B and starting the recorder simultaneously. The run was continued until the system had stabilized. At this time the time history trace on the recorder would have returned to the original zero position. Each run was made at least twice in order to obtain sufficient data for averaging experimental errors.

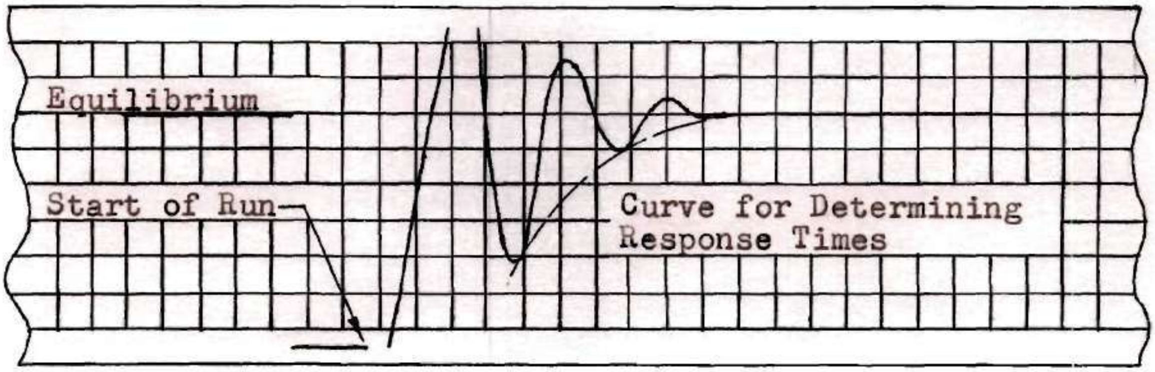
Calibration

The procedure followed in calibrating the system was similar to the procedure used in making runs; however, the calibration was independent of the reservoir pressure. The only requirements for the calibration was that the mercury be initially within the region enclosed by the variable capacitor and that the grid voltage on the first d-c amplifier be the same as that used for the runs. The initial voltage was set in conjunction with the Sanborn amplifier gain until the desired sensitivity was obtained. A zero trace was then made on the recorder. Valves B and C were closed and line pressure dropped by opening valve D. Valve C was then opened and closed in measured steps until equilibrium was restored. By comparing these pressure steps with the corresponding trace deflections the entire system was calibrated. This type of calibration showed in every case that the recording system was linear over the range where measurements were desired.

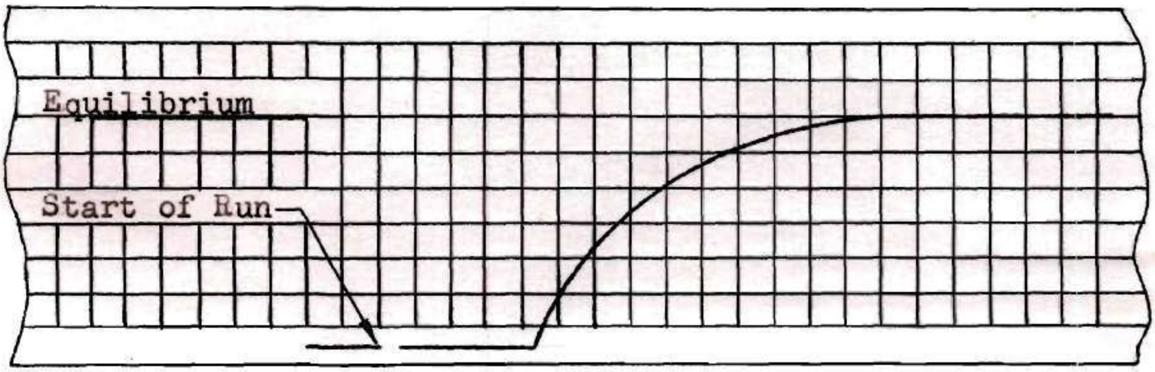
Because of the high sensitivity required to measure the response time (within one per cent of the reservoir pressure) it was impossible to obtain a complete time history of the movement of the mercury. However, since only the last one or two millimeters of mercury were of interest, this was no imposition. In the initial portion of the run the recorder stylus remained against the stops; then, as the pressure approached equilibrium the last increment of mercury movement was recorded.

Reduction of Data

The data reduction consisted in determining the response time for each run. A typical run is shown in Fig. 8. From the calibration runs the response times corresponding to τ, τ_1 and τ_2 were determined. For the time histories having an exponential form these distances were measured from the equilibrium trace to the point where they intersect the time history of the run. For the oscillatory time histories, these distances were measured from the equilibrium trace to the lower envelope of the damped oscillation. The lower envelope of the curve was chosen because it gave conservative values of the response times. The operating speed for the Sanborn recorder was two and one-half and twenty-five millimeters per second. The response time was determined by measuring the length of the run and dividing by the appropriate time constant. Response time for this report was defined as the time required for the pressure to reach a point within one per cent of its equilibrium value; however, calculations were also made for two and one-half, and five per cent for use where lower accuracies could be tolerated.



Oscillatory Response



Exponential Response

Figure 8. Typical Sanborn Recorder Traces

CHAPTER IV

DISCUSSION OF RESULTS

The results of this investigation are given in Fig. 9 through Fig. 15. In these plots the effects of capillary tube diameter, capillary tube length, connecting tube length, reservoir pressure and initial line pressure on the response time are given. Since the results obtained for response times of two and one-half and five per cent were considered to be of minor importance, these plots are not discussed but merely placed in the Appendix for reference. These curves differ qualitatively from the one per cent curves in that they are displaced toward zero. The test points shown on these plots are the average values obtained from two or more tests. An individual discussion of the effects of each of the important parameters follows.

Capillary tube diameter.--Capillary tube diameter is an extremely critical factor in the design of the pressure system. The geometric considerations usually require that this parameter be quite small. A study of Fig. 9 through Fig. 11 shows that for tubing diameters of less than 0.042 inches there is a very rapid increase in response time. It is interesting to note that the response time variation for tubes having diameters larger than 0.042 inches actually increase for the

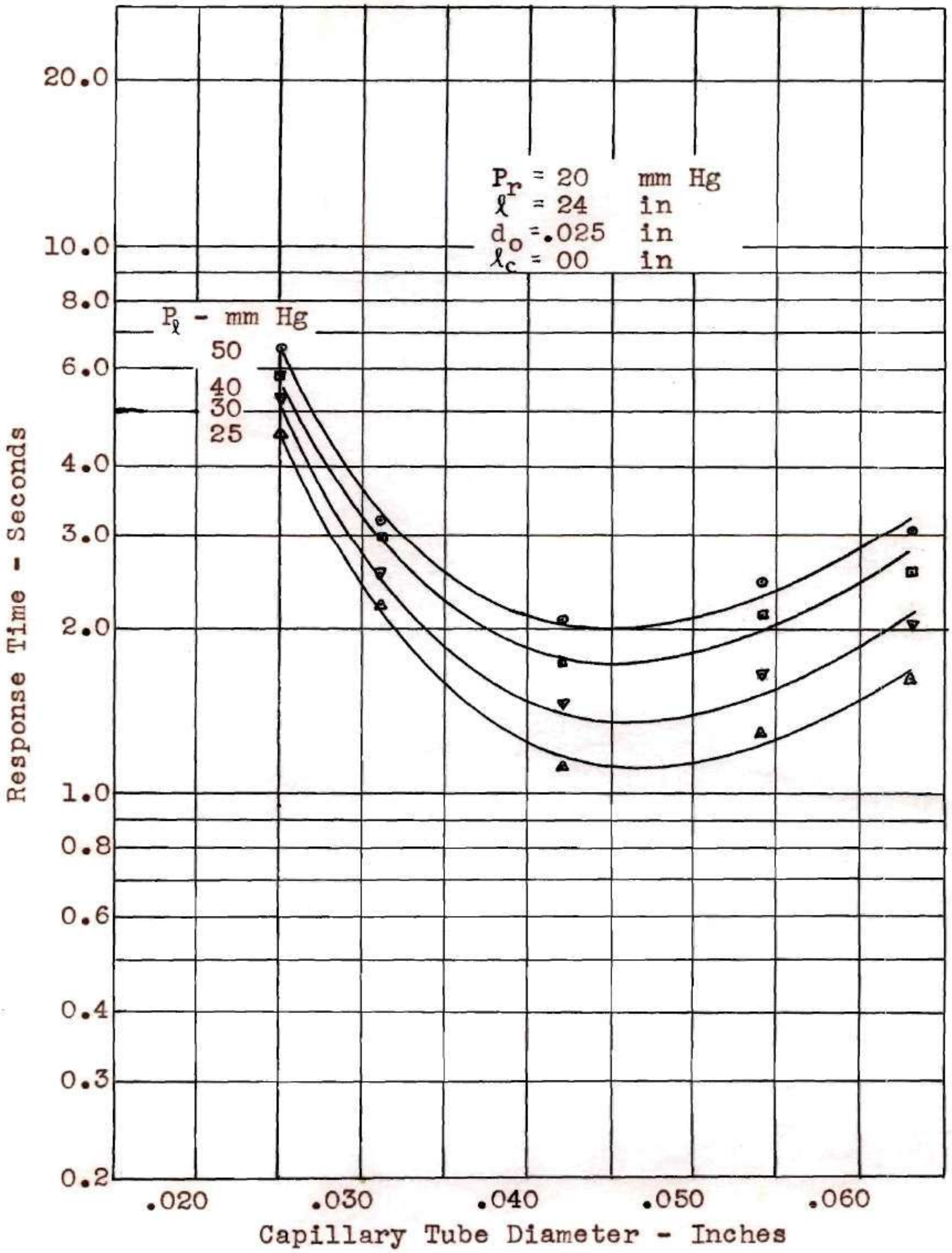


Figure 9. Response Time Variation With Capillary Tube Diameter - $\tau_{.99}$

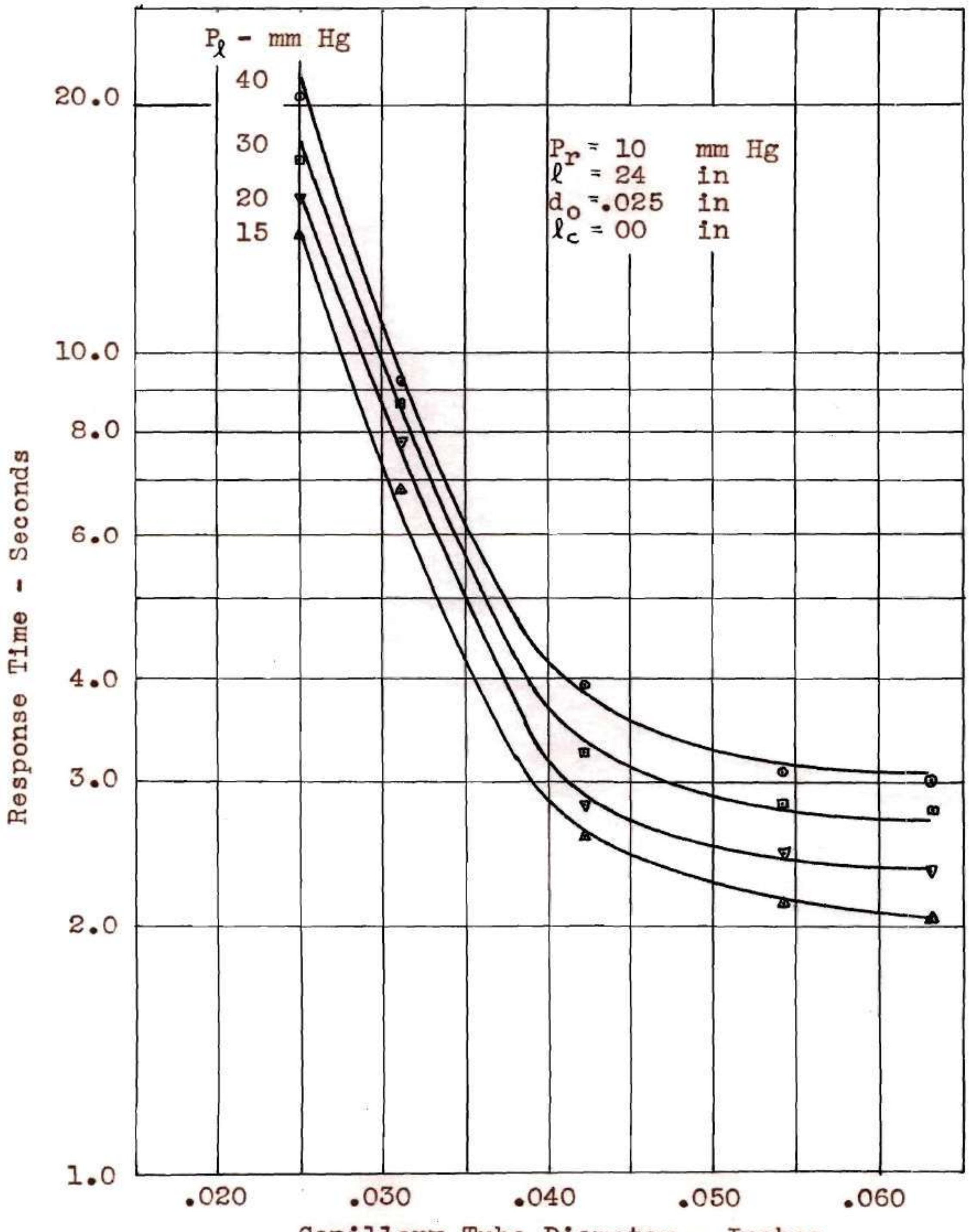


Figure 10. Response Time Variation With Capillary Tube Diameter - τ

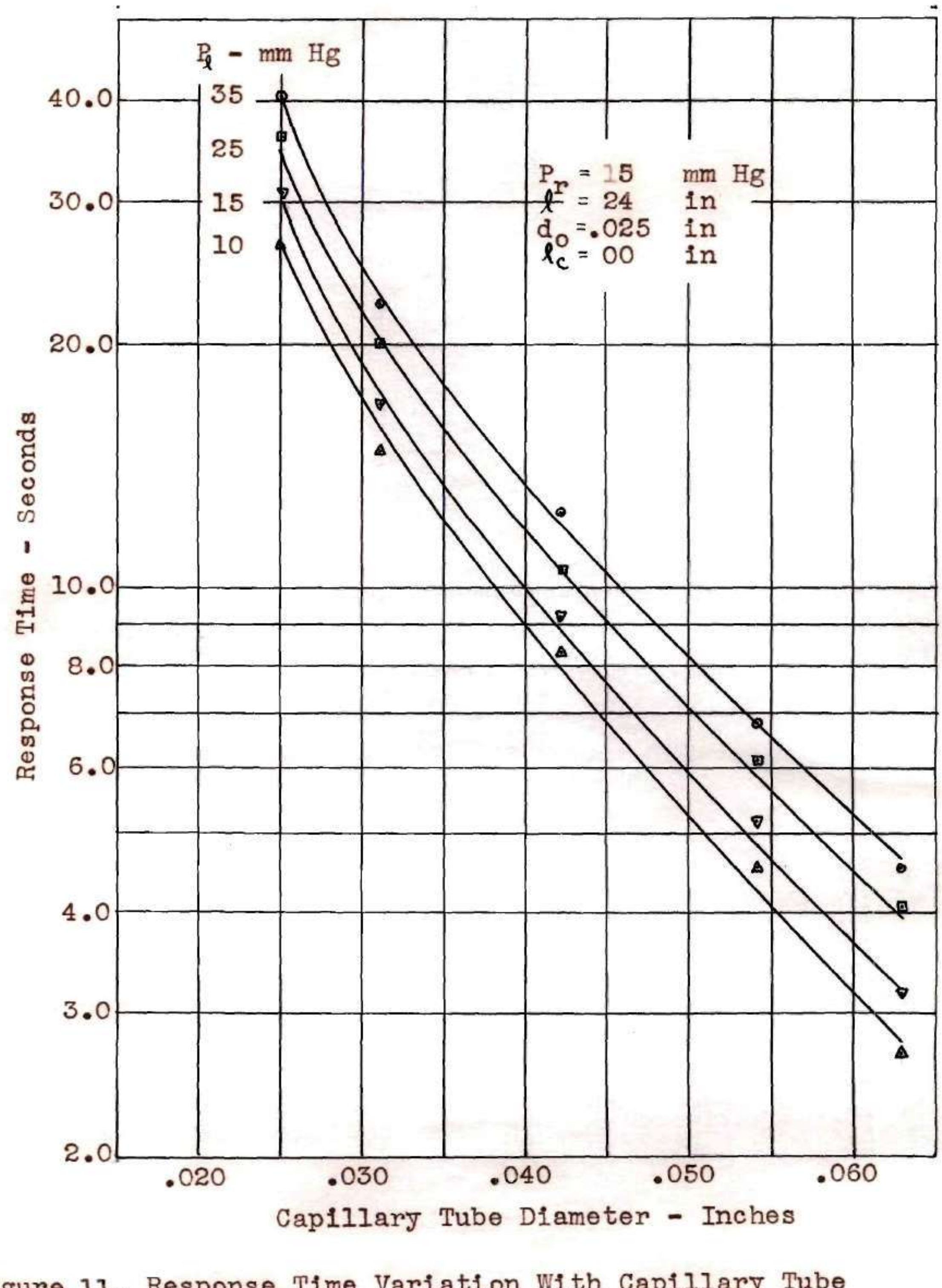


Figure 11. Response Time Variation With Capillary Tube Diameter - τ

higher reservoir pressures. This phenomena can be explained by investigating the damping characteristics of the system. For diameters larger than 0.042 inches the response to the step function was oscillatory while for the smaller diameters the response had an exponential form. The damping ratio, which is defined as the ratio of the actual damping to the critical damping, then varies from a value greater than one to a value less than one as the tube diameters are increased from 0.025 inches to 0.063 inches. This result indicates that the optimum tube size should have a damping ratio near one.

At the lower reservoir pressures the system tended to oscillate about a point below equilibrium and then rise exponentially to the equilibrium position when the oscillatory mode had dissipated. This accounts for the increase in optimum tube size as the reservoir pressure is lowered. This data compares favorably with that in reference 2; however, there was no indication of oscillation in this earlier work. Instead the response time decreased slowly for tube diameters greater than 0.042 inches and increased rapidly when the smaller tube diameters were used. The variance in the data probably can be attributed to the different types of pressure sensitive instrument used in the two sets of tests.

Capillary tube length.--Increasing the length of the capillary tubing resulted in an increase in damping of the system. These results are shown in Fig. 12. The response curves did not over shoot the equilibrium position for any lengths four feet or longer which accounts for the crossing of the curves having tube diameters larger than 0.042 inches. These data also show a rapid increase in slope with a decrease in tube diameter. This trend was also apparent in the work done in reference 2.

Connecting tube length.--The effects of connecting tube length are shown in Fig. 13. These curves bear a close resemblance to those obtained for variable capillary tube length. Since the connecting tubing had an inside diameter of 0.125 inches, the primary effects of this parameter was to increase the mass of air in the pressure lines. For the larger tubing with its low damping this effect was negligible and the slope of the curves was approximately equal to zero. However, as the tube size was reduced and the viscous effects became dominant, the response time increases rapidly.

Reservoir pressure.--The variation of response time with reservoir pressure is shown in Fig. 14. It was shown in reference 2 that halving the reservoir pressure doubled the response time. This phenomena was found to hold approximately true for the present tests where no oscillations occurred during the runs. For the larger tubes where oscillations were present this criterion failed.

Initial line pressure.--The effects of the initial line pres-

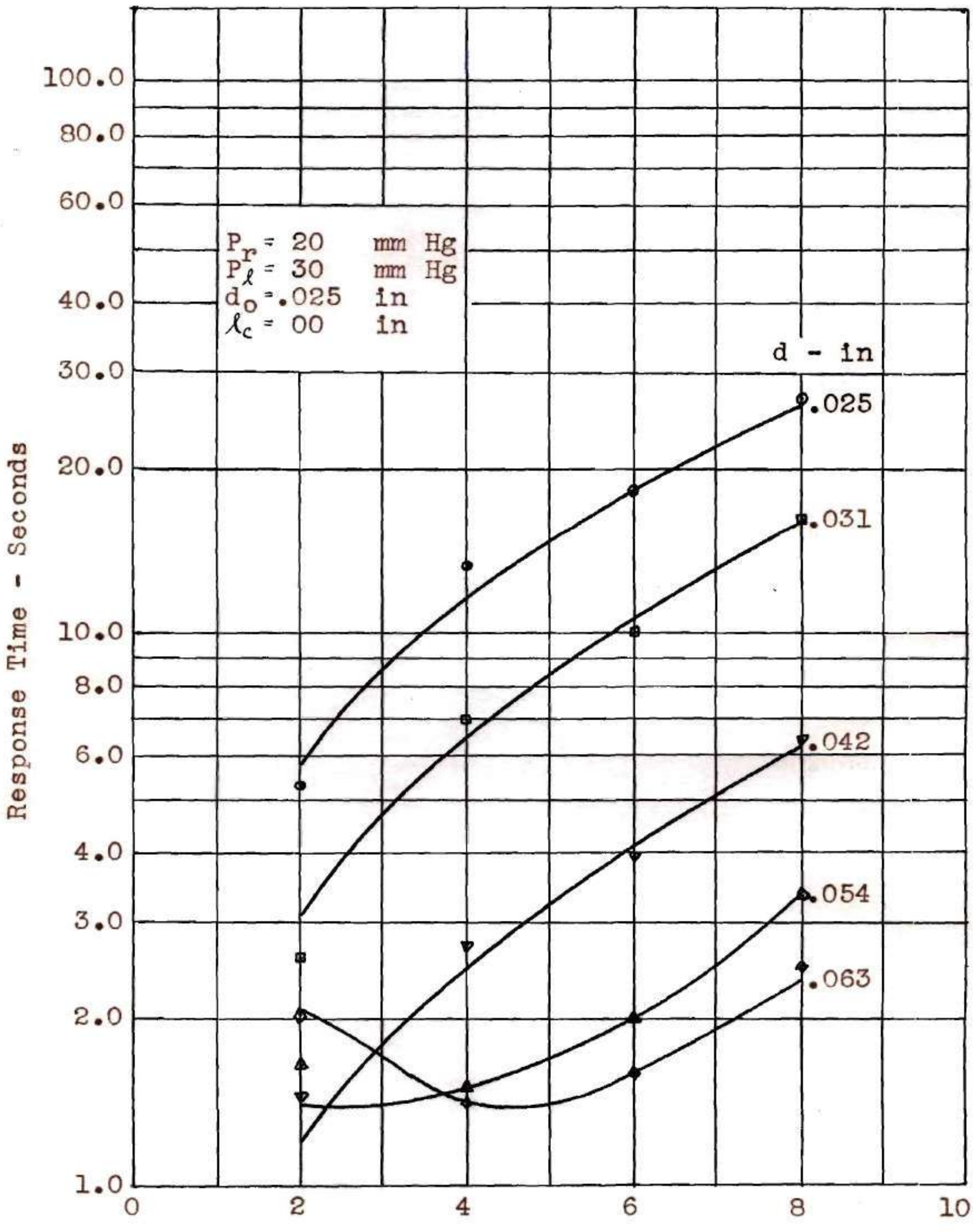


Figure 12. Effect Of Capillary Tube Length On Response Time - τ

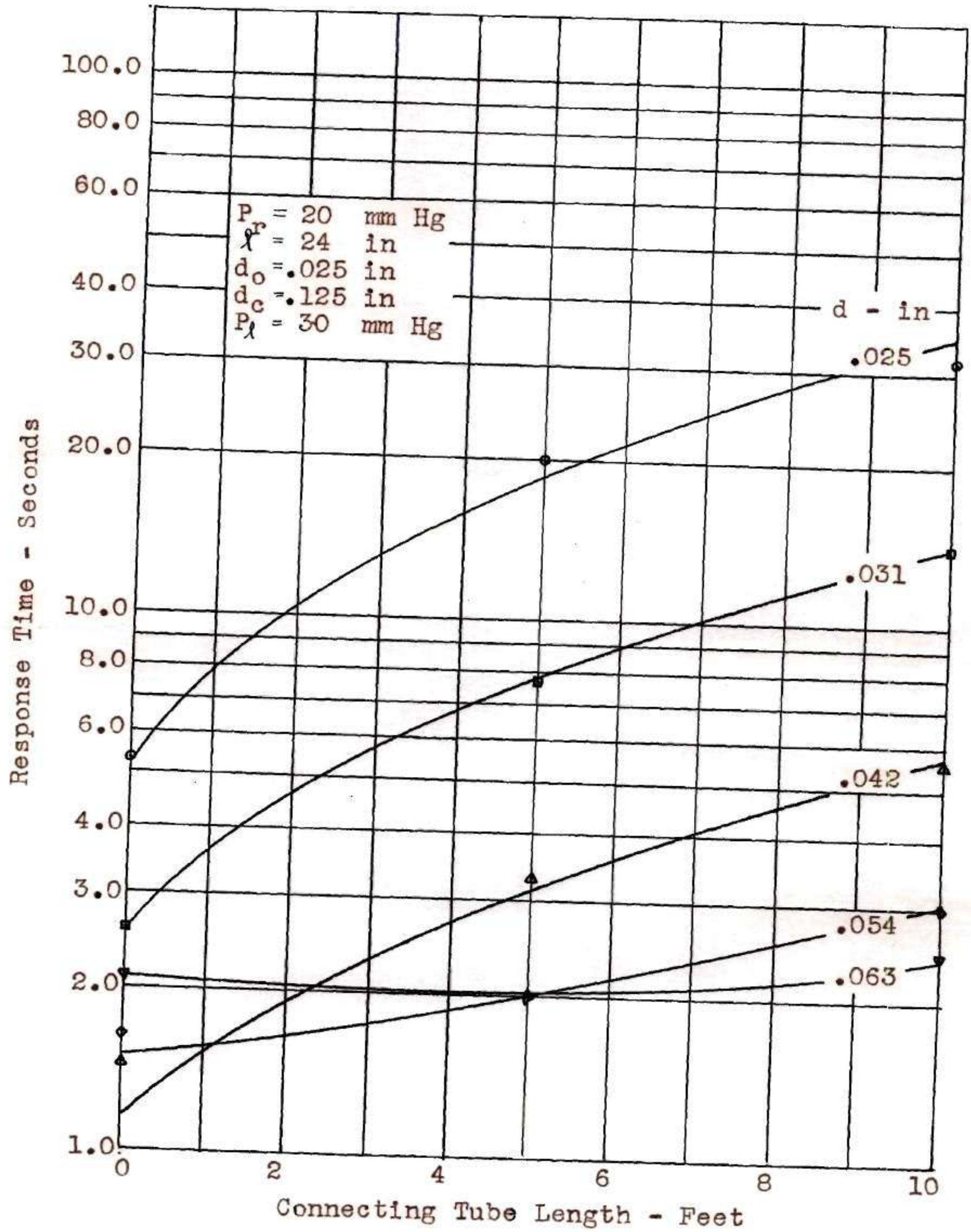


Figure 13. Effect Of Connecting Tube Length On Response Time- τ

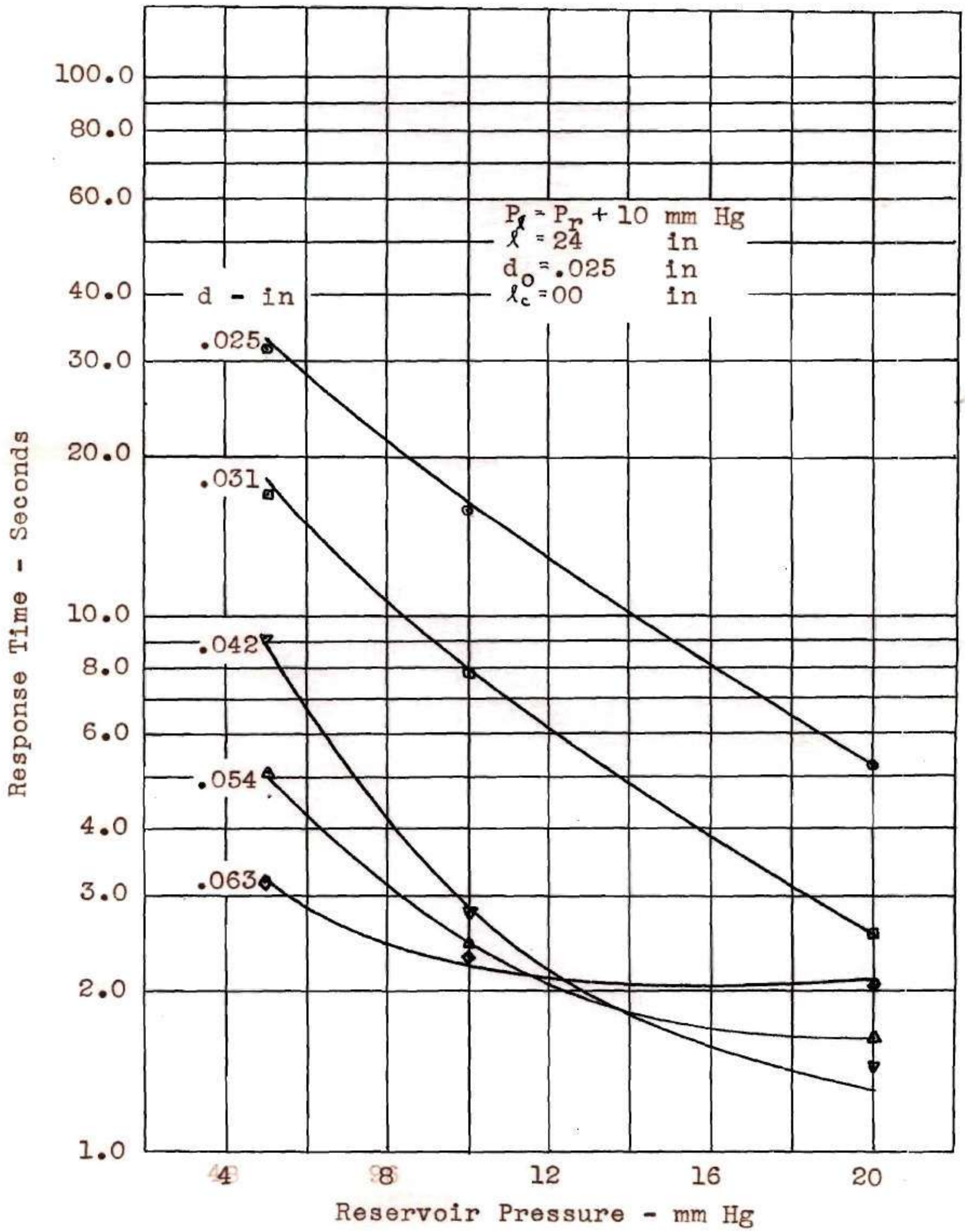


Figure 14. Effect of Reservoir Pressure on Response Time - τ

sure on the response time were found to be negligible. The slopes of the curves shown in Fig. 15 are very small for the large tube diameters and increase only slightly when the tube diameter is decreased. The type of response obtained from the pressure system shows clearly why this phenomenon occurs. Since the response is exponential in form, the slope is initially steep and then decreases as equilibrium is approached. The response time is therefore primarily dependent on the last few millimeters of travel.

Other parameters.--The parameters not evaluated in this analysis are orifice diameter and length, connecting tube diameter and volume of the pressure sensitive device. Since the variation of the important parameters in this work showed the same trends as in the case of reference 2 it is felt that the effects of the parameters not varied in these tests will be similar to those in reference 2. A summary of these effects is given below.

> Orifice Effect. The orifice diameter should not be less than one-half the model tubing diameter, with slight advantages to be gained as the orifice diameter approaches the tubing diameter.
> Connecting Tubing Diameter Effect. The inside diameter of the connecting tubing should be from 1-1/4 to 1-1/2 times the inside diameter of the model tubing.
> Volume Effects. The capacity of the sensing-element reservoir should be minimized.

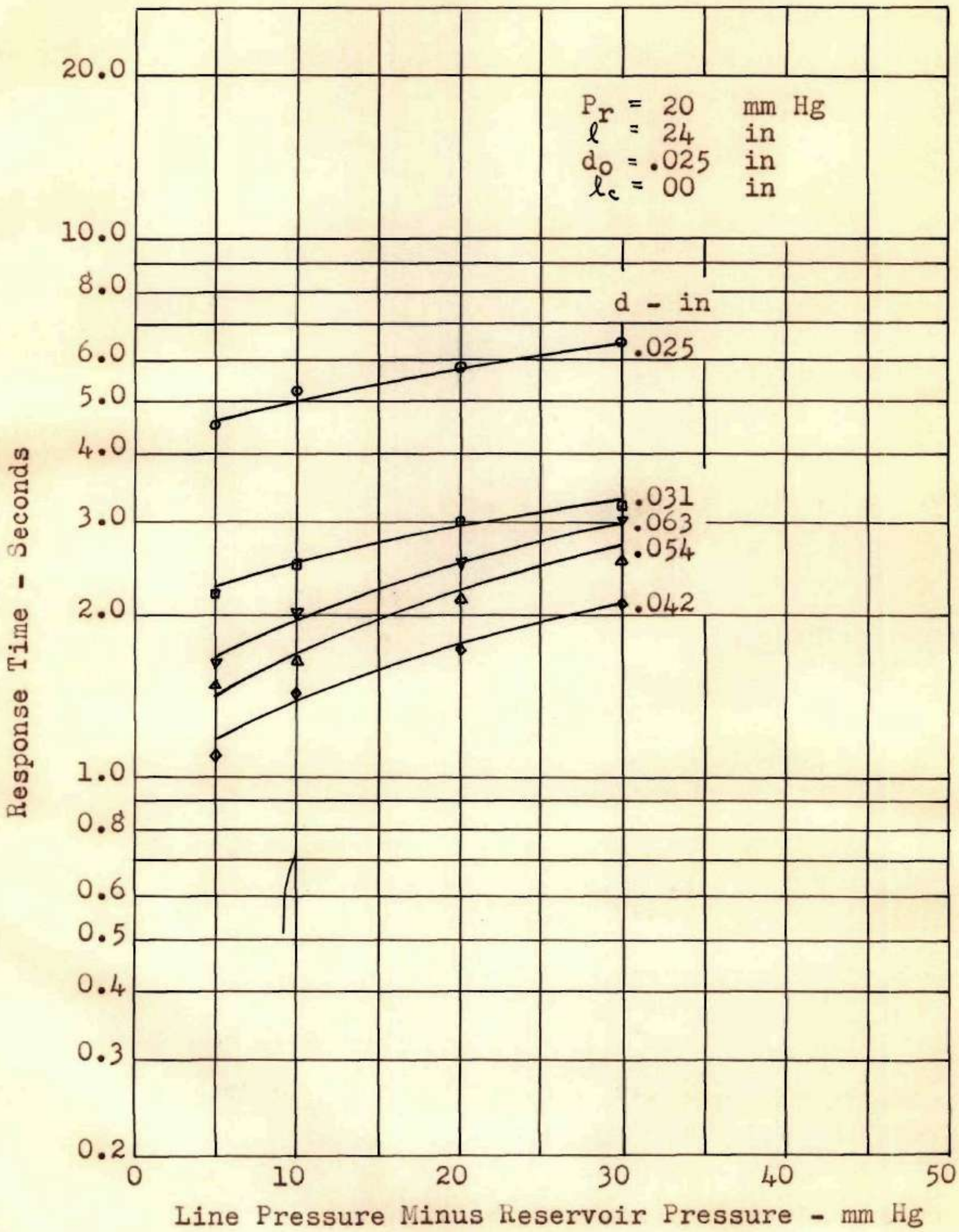


Figure 15. Effect of Line Pressure on Response Time - τ

CHAPTER V

CONCLUSIONS

Based on the data obtained in this experimental analysis, the following conclusions have been drawn.

1) The model tubing diameter should be as large as possible where reservoir pressures are less than ten millimeters of mercury. For higher pressures a tube in the neighborhood of 0.042 inches is recommended.

2) The model tubing length should be held to a minimum.

3) Minimum lengths of connecting tubing should be used.

4) The initial line pressure has no appreciable effect on the response time of the system; however, it is advantageous to set the line pressure as close to the equilibrium pressure as feasible.

CHAPTER VI

RECOMMENDATIONS

As previously mentioned, all the parameters which affect the response time of a pressure instrumentation system were not covered in this analysis. The factors which were omitted were

1. Volume of the pressure sensitive device
2. Orifice diameter and length
3. Connecting tube diameter.

In order to complete the work done in this report it is recommended that these parameters be studied.

There are several other possibilities for studies in this field. They are as follows:

1) An investigation to determine the effects on the response time of pressure sensitive devices containing other manometer fluids.

2) An investigation to determine the effects on the response time of reservoir pressures of less than five millimeters where continuum flow no longer exists.

3) An investigation to determine the effects on the response time of variable diameter tubing in a pressure system.

4) An investigation to determine the effects of line pressures less than reservoir pressures on the response time.

APPENDIX

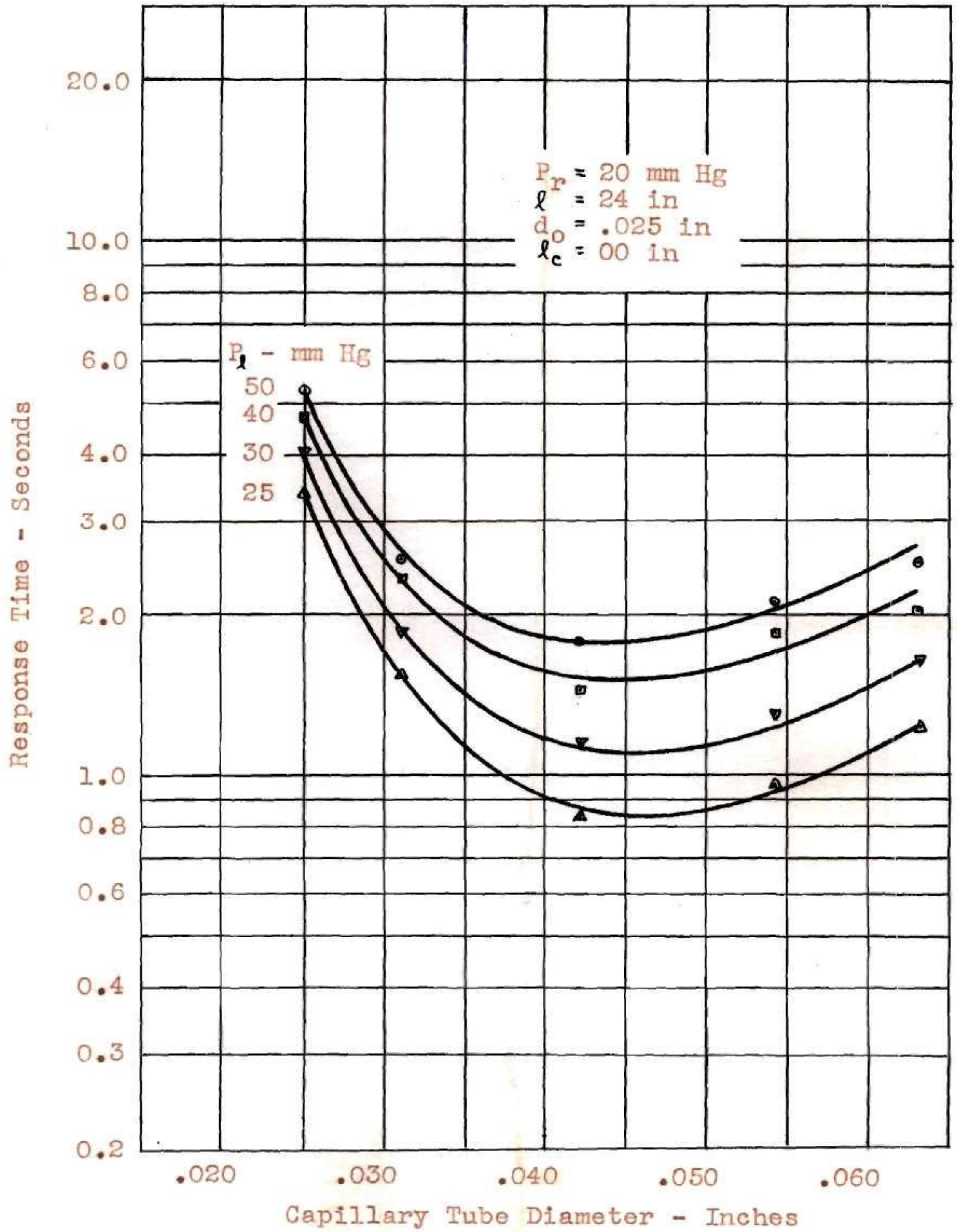


Figure 16 Response Time Variation With Capillary Tube Diameter - τ_1

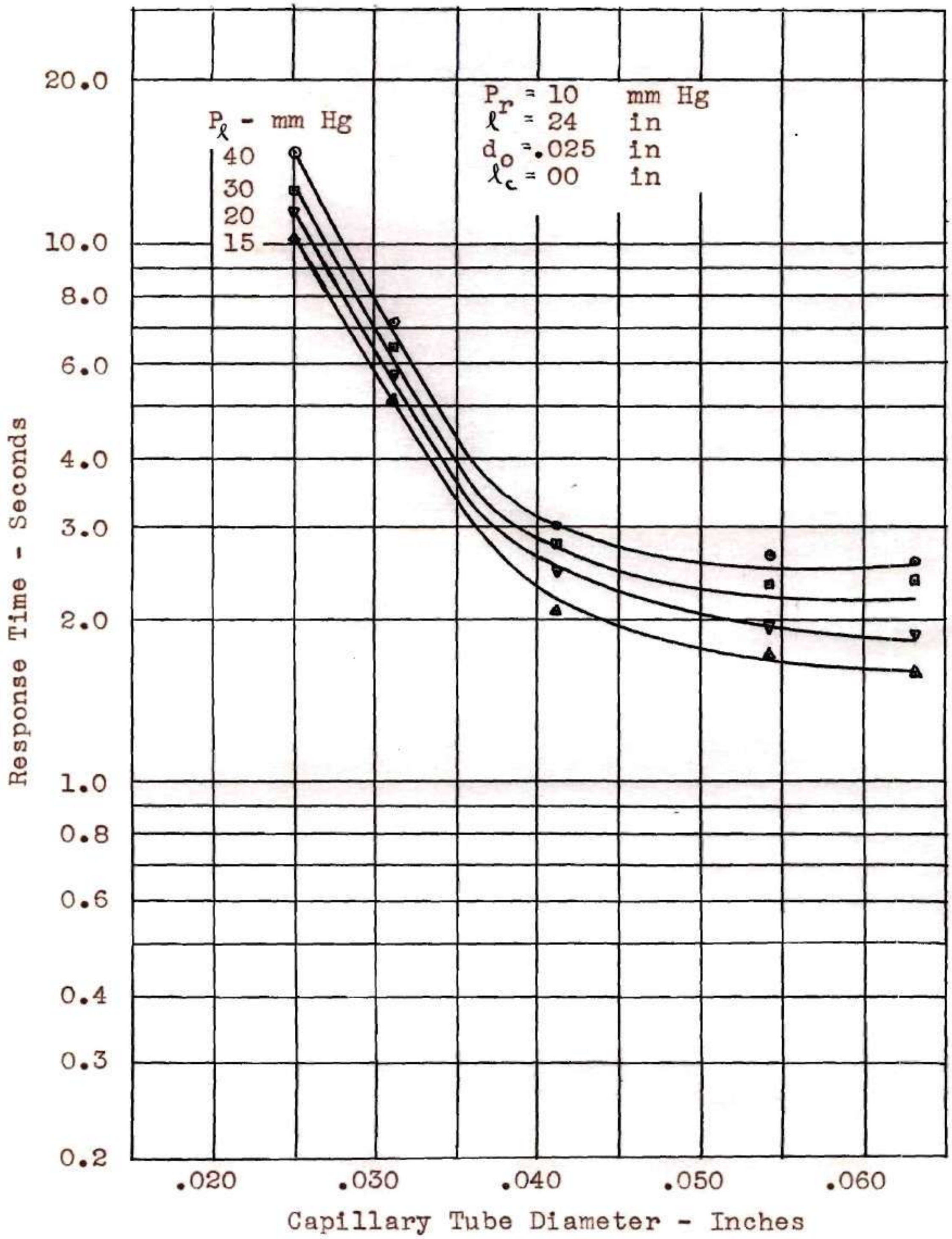


Figure 17. Response Time Variation With Capillary Tube Diameter - τ_1

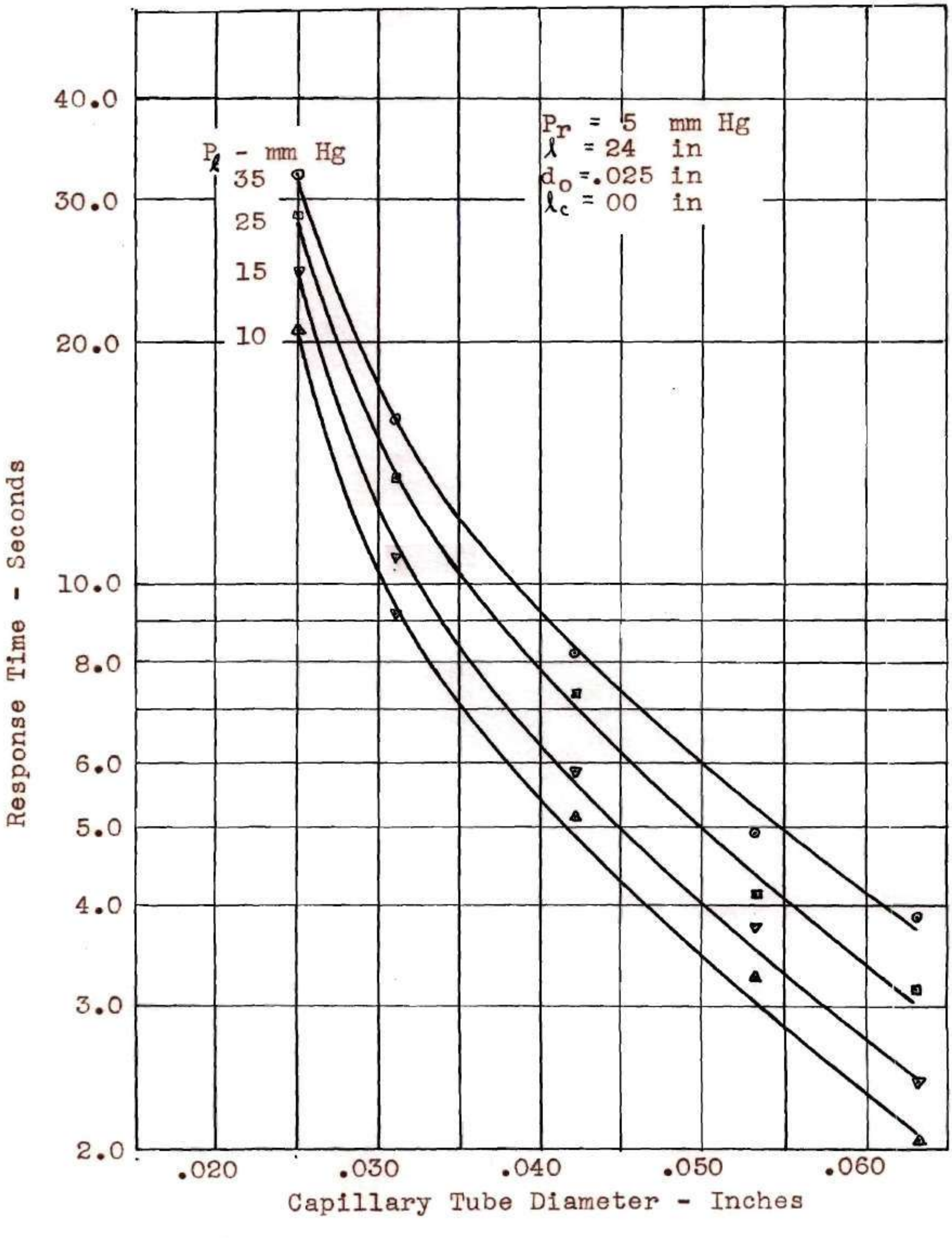


Figure 18. Response Time Variation With Capillary Tube Diameter - τ_1

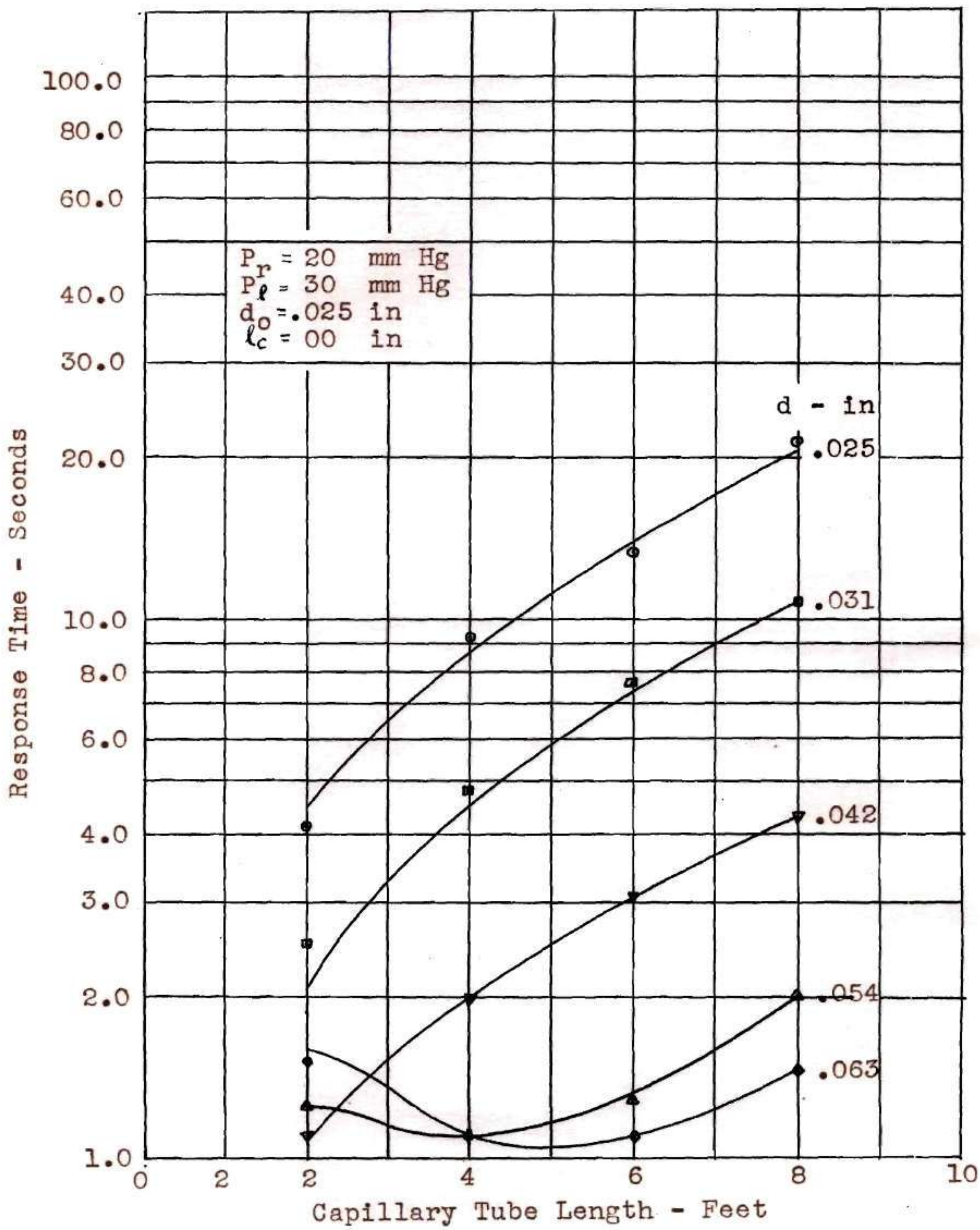


Figure 19. Effect Of Capillary Tube Length On Response Time - τ_1

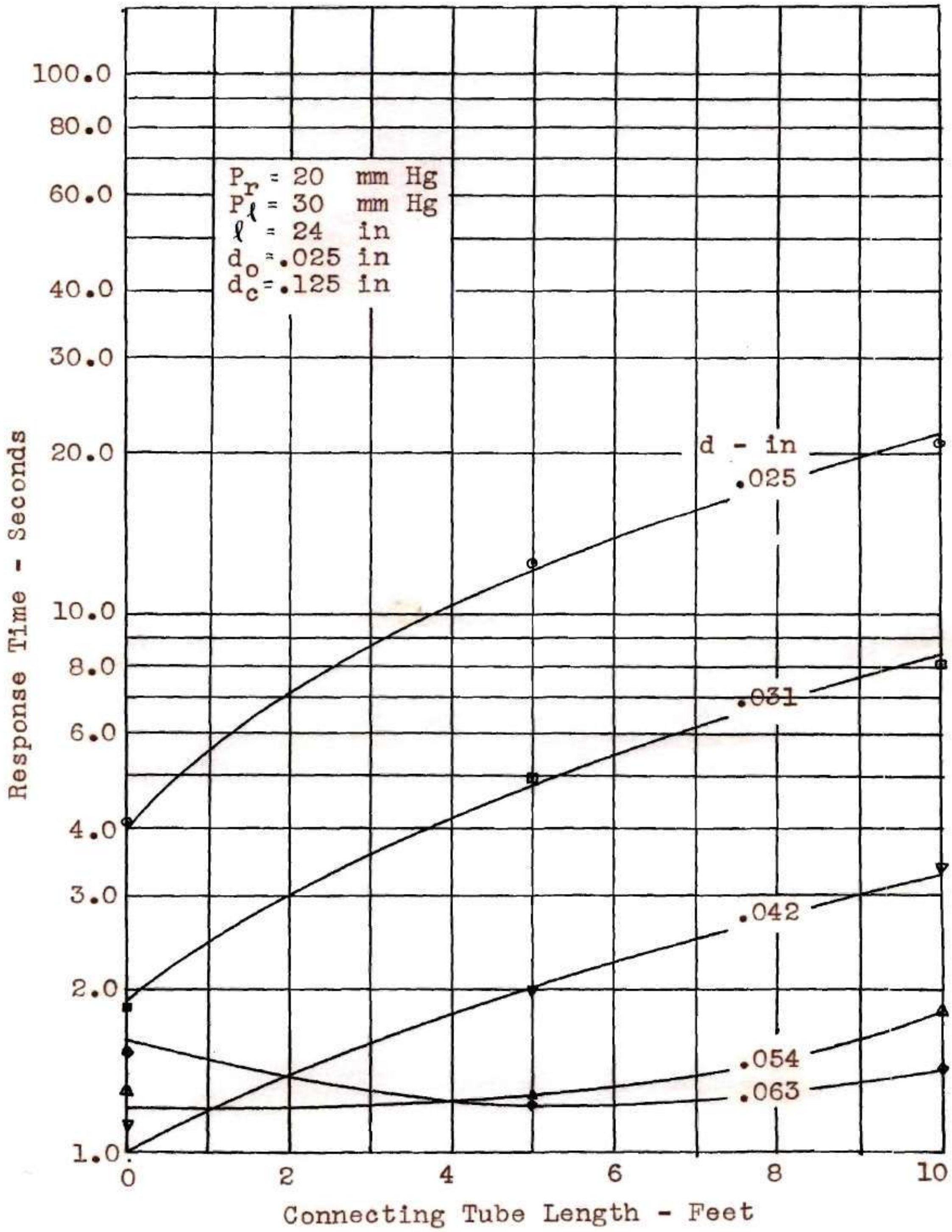


Figure 20. Effect Of Connecting Tube Length On Response Time - τ_1

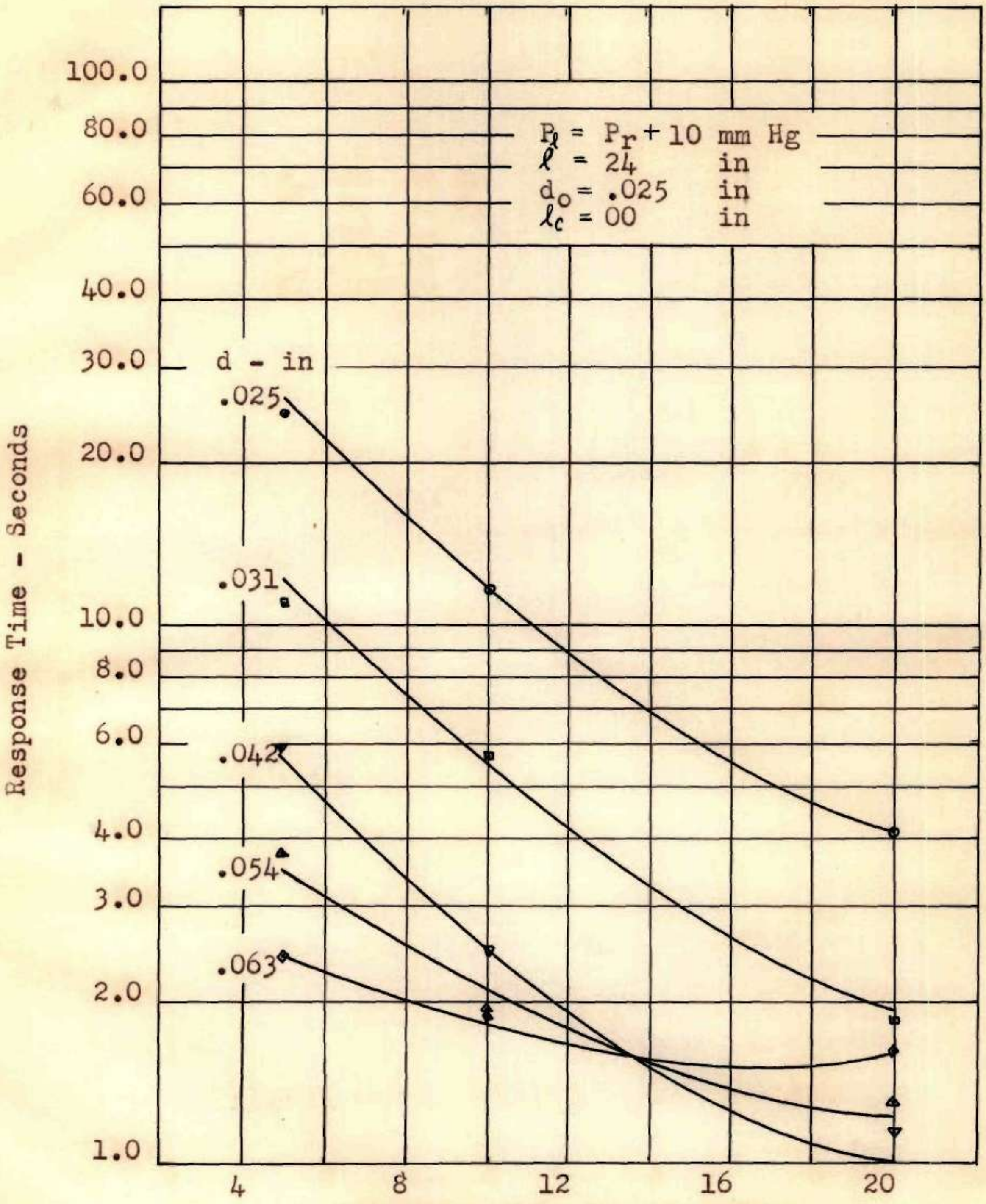


Figure 21. Effect of Reservoir Pressure on Response Time - τ_1

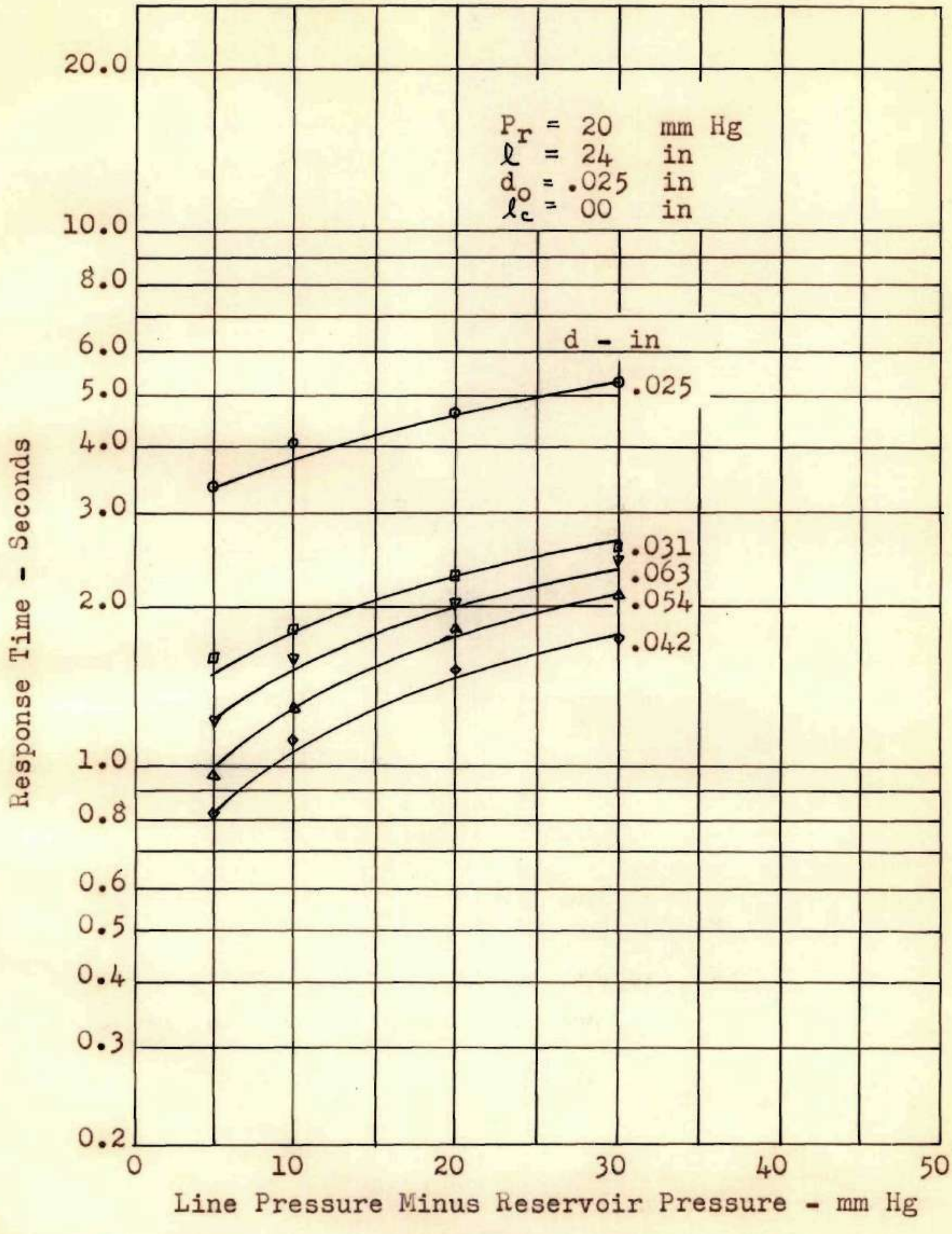


Figure 22. Effect of Line Pressure on Response Time - τ_1

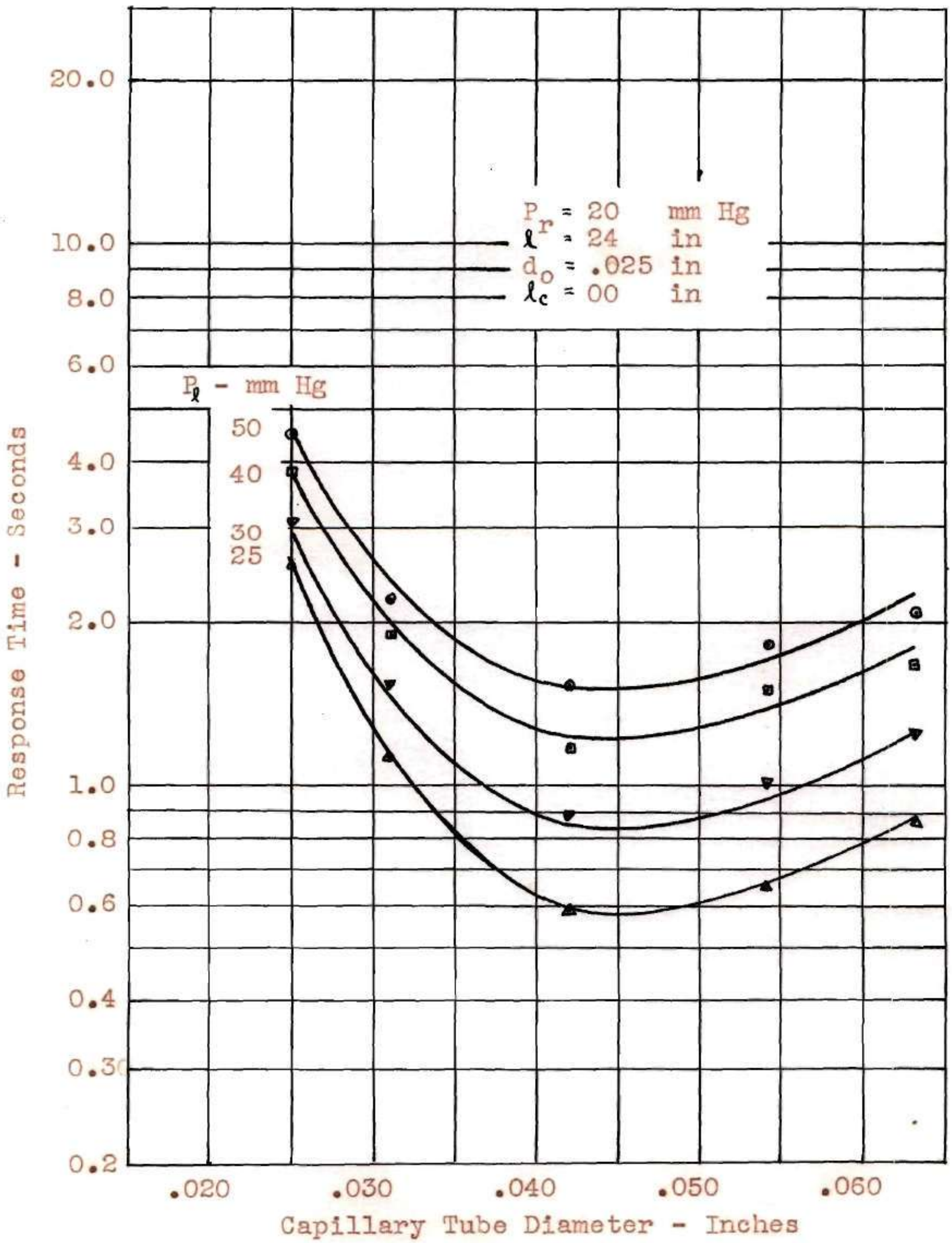


Figure 23. Response Time Variation With Capillary Tube Diameter - τ_{2}

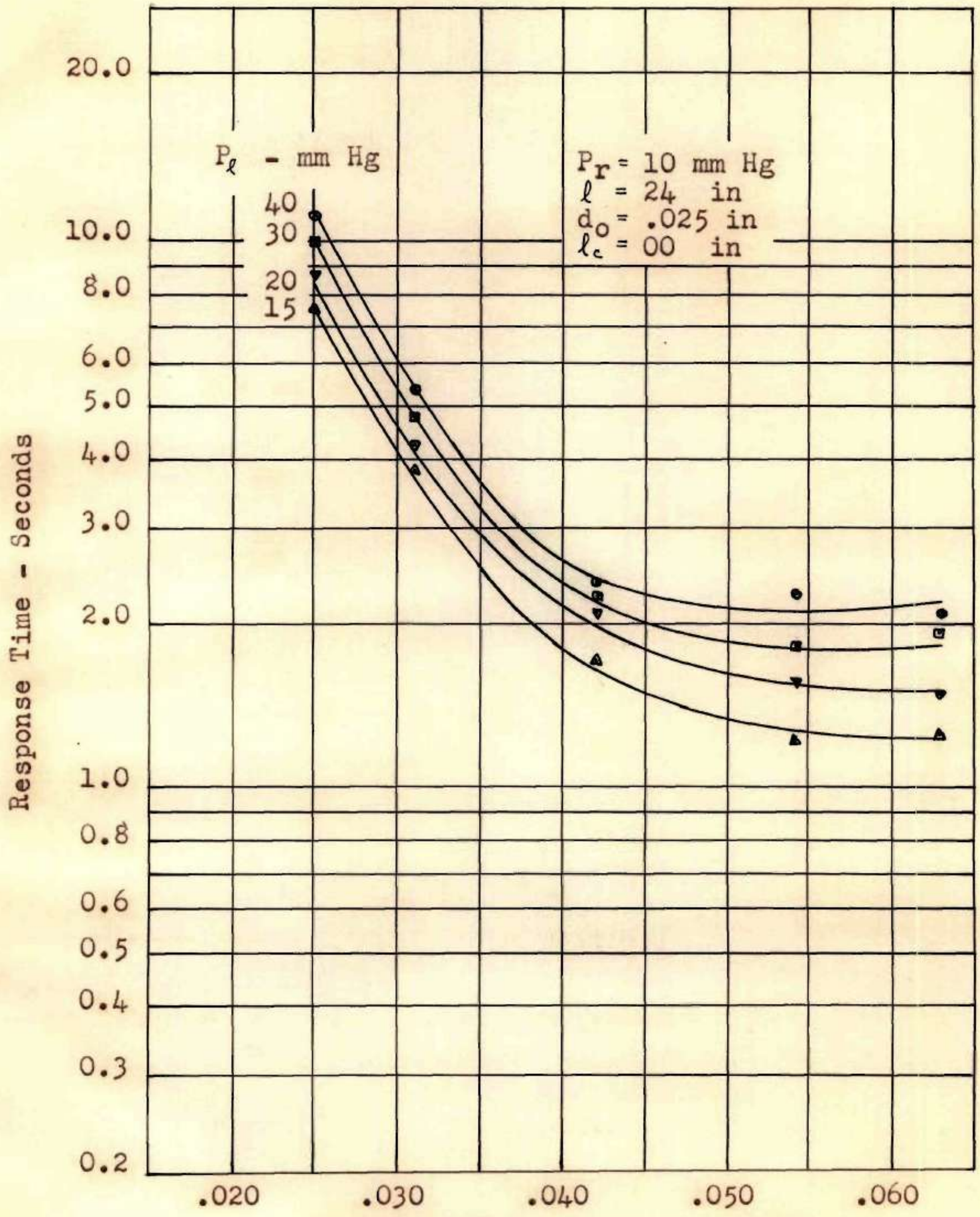


Figure 24. Response Time Variation With Capillary Tube Diameter - τ_2

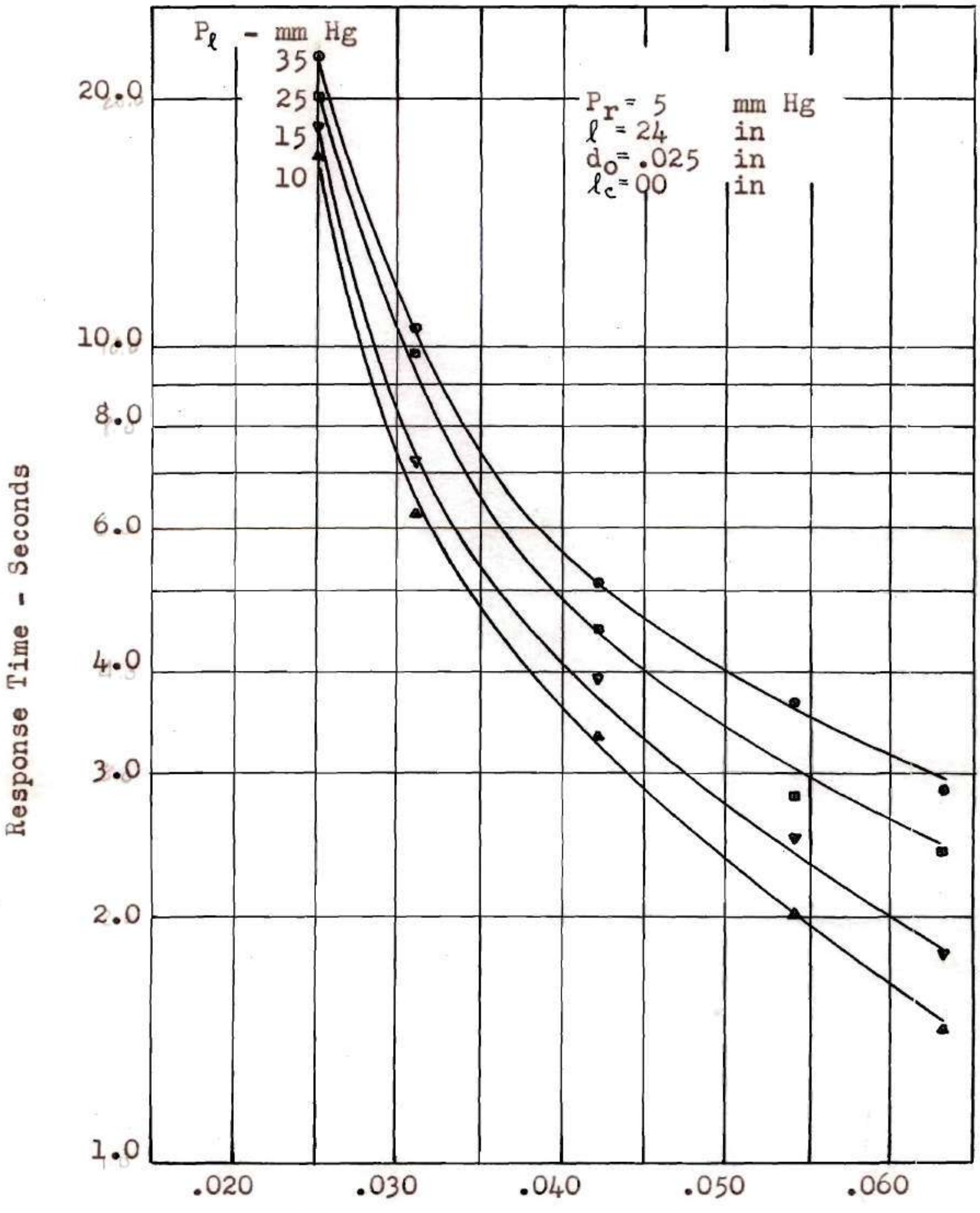


Figure 25. Response Time Variation With Capillary Tube Diameter - τ_2

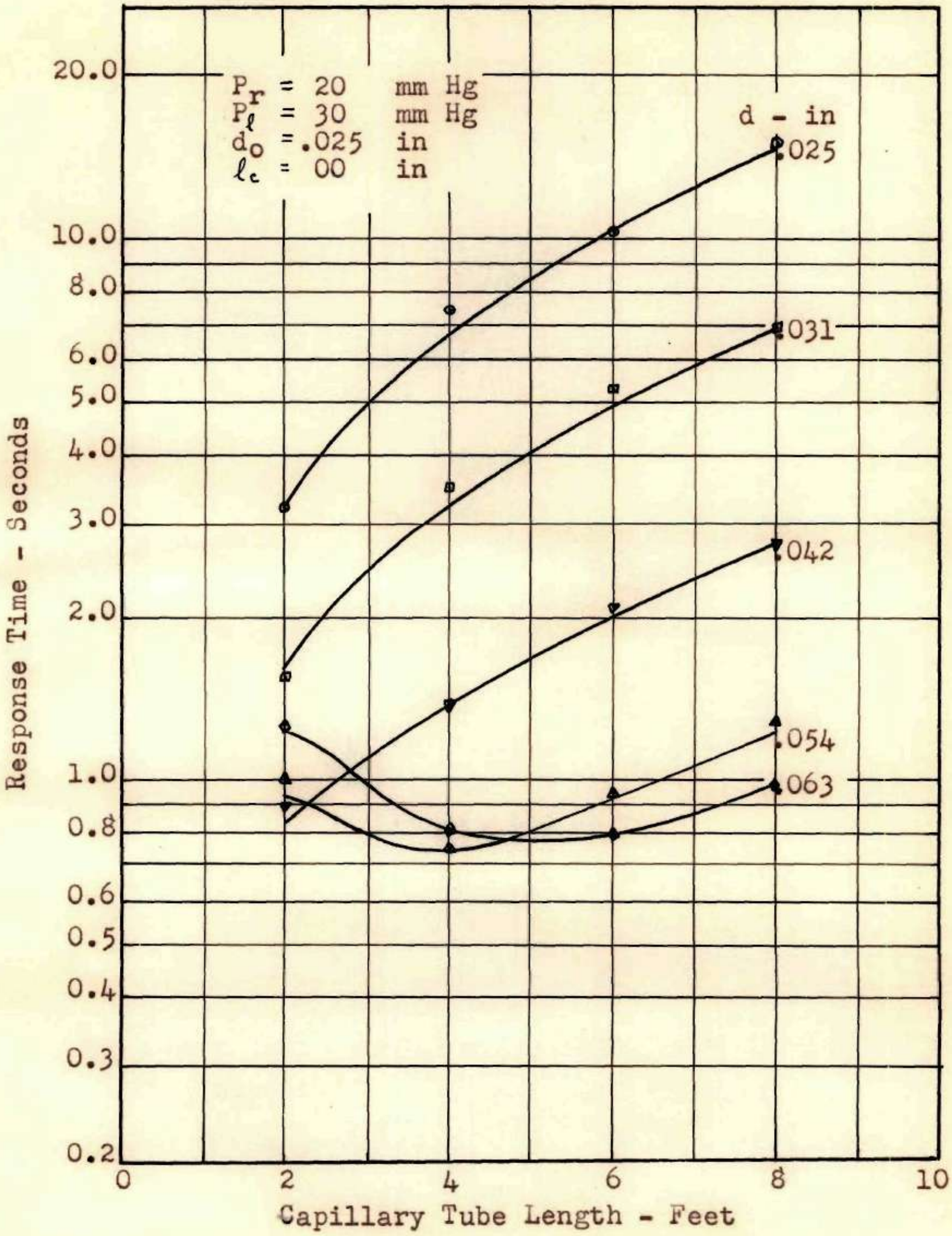


Figure 26. Effect of Capillary Tube Length on Response Time - τ_2

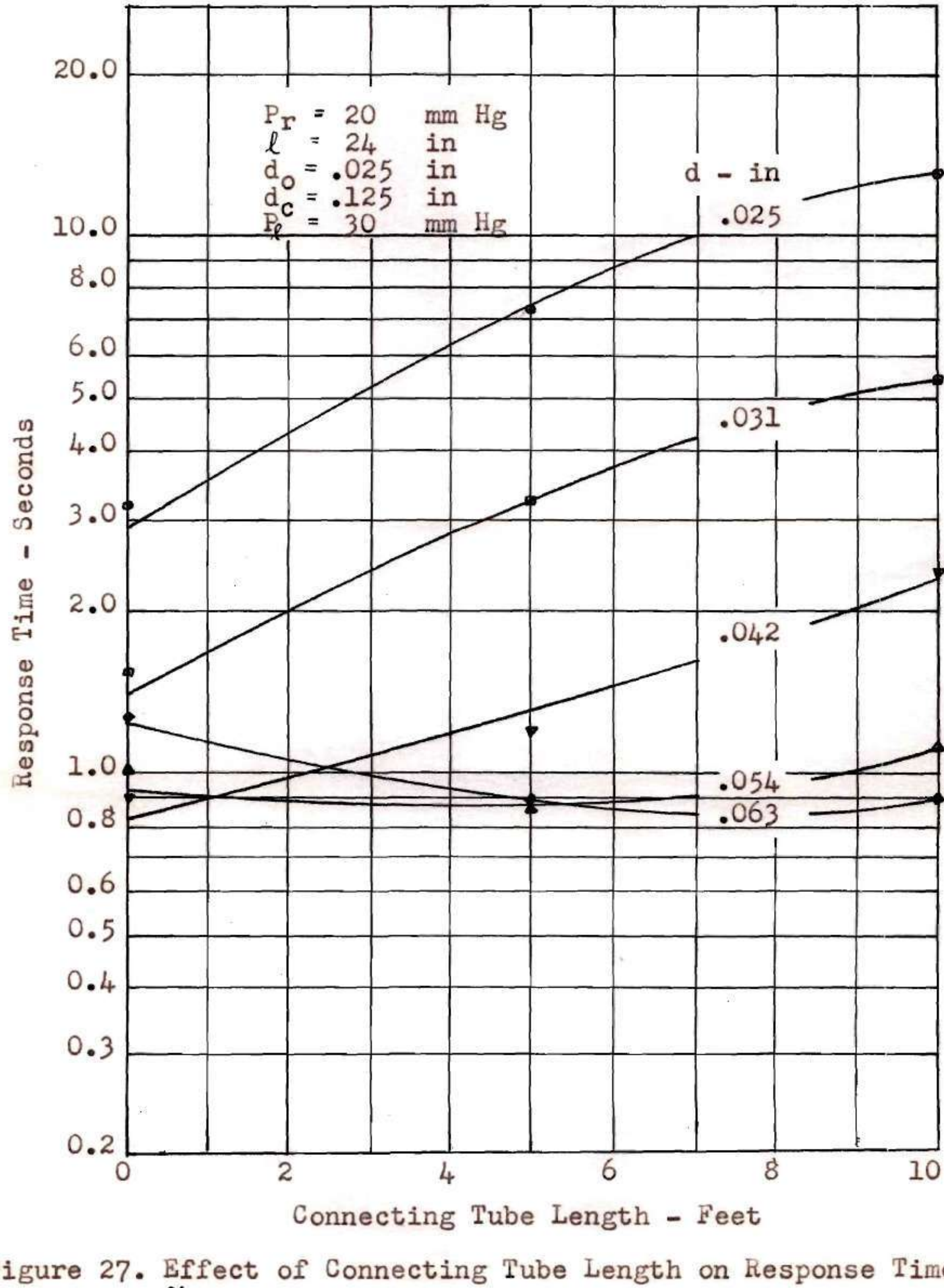


Figure 27. Effect of Connecting Tube Length on Response Time - τ_2

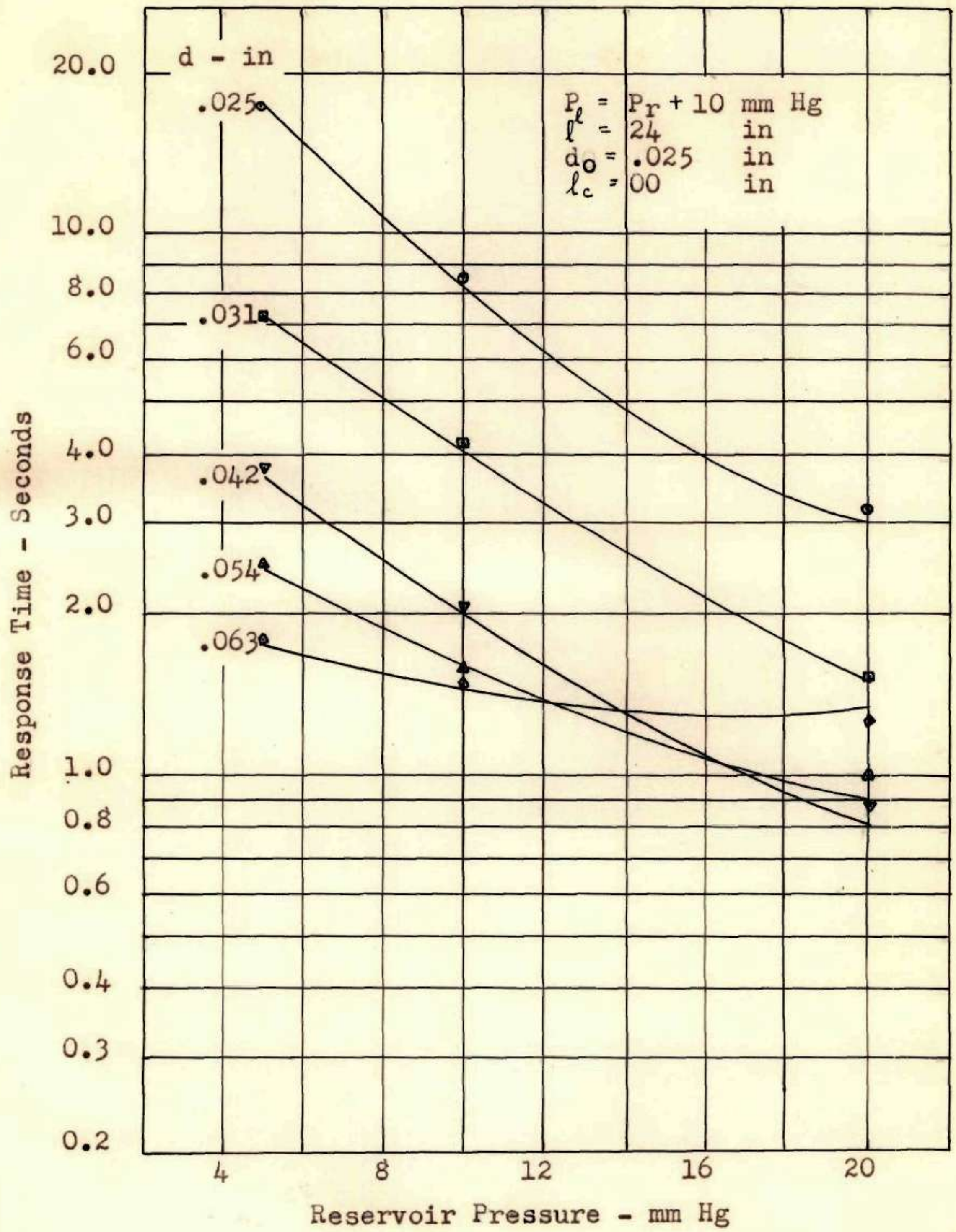


Figure 28. Effect of Reservoir Pressure on Response Time - τ_2

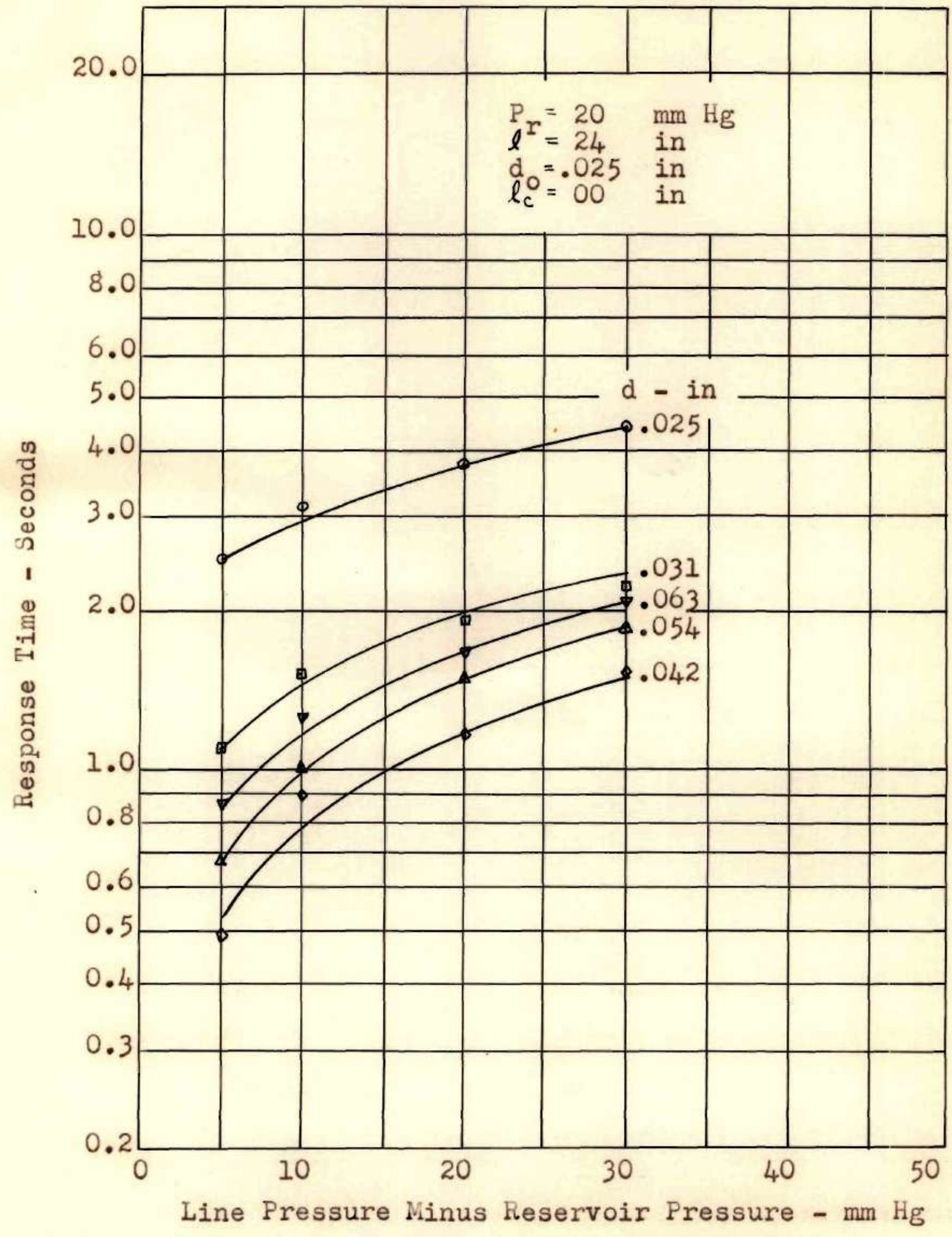


Figure 29. Effect of Line Pressure on Response Time - τ_2

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2- Ducoffe, A. L.; An Analytical and Experimental Investigation of the Response Time for Quasi-Steady, Viscous, Compressible Flow in Capillary Tubing Initially Subjected to a Step Function in Pressure; Ph.D. Thesis; University of Michigan; 1952.